AN ABSTRACT OF THE THESIS OF

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Automation of Capacitor Discharge Welding (CDW) has not been investigated in industry due to the limited understanding of the process. The US Department of Energy's Albany Research Center (ALRC) has done an extensive study of the process and reported applications of welds in the manufacture of electro-mechanical products such as relays and circuit-breakers.

The main purpose of this work was to investigate automation of the load/unload cycle of CDW. An automatic CDW machine was built with real-time quality monitoring capabilities. Tooling and fixtures were fabricated for joining silver to brass components used in a circuit breaker assembly. A machine controller was used to automatically sequence the process and the actuators. Computer-based instrumentation was developed for on-line data acquisition and quality monitoring of the weld. This demonstrational set-up shows that the equipment can be compact and the process can be easily automated for high production rates. The automation architecture developed can be used as a general model for automating CDW operations in other environments.

The automated CDW system was tested by welding silver contacts to brass brackets at different parameter settings. Metallographic examination of the resultant

capacitor discharge (CD) welds (made by the automated CDW system) revealed the formation of continuous metallurgical bonds between silver and brass. A comparison of CD welds made by the manual and the automated system was performed to determine the effect of CDW automation on weld quality. The welds were also found to be superior to resistance welds.

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Development of an Automated Capacitor Discharge Welding System

by

Srinivas M. Patnaik

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DEVELOPMENT OF AN AUTOMATED CAPACITOR DISCHARGE WELDING SYSTEM

1. INTRODUCTION

Automation is defined as the technology concerned with the application of mechanical, electronic, and computer-based systems to operate and control production (Groover, 1987). This revolution started over three decades ago. Robotic technology is at the leading edge of the current race towards productivity and improved product quality. The advantages of automation include improved productivity, better product quality, and improvement in the status of workers.

Welding is an effective and economical method for joining most commercial metals. Welding processes have been found more difficult to automate and control compared to other manufacturing processes (Lane, 1987). However, recent technological developments in the field of electronics, computers, and robotics have opened possibilities for the introduction of flexible, low-cost automation of welding processes. Arc welding robots are used in large-volume production lines for automobiles (Norrish, 1992). According to Eichhorn (1985), in the future, automated welding will be associated with small, mass-produced units for which the loading of assembly parts to be assembled and unloading the finished assembly can be integrated relatively easily into the production line.

Many welding processes are labor intensive and an analysis of welding costs shows that some 70 to 80% of the total cost may be accounted for by direct labor (Norrish, 1992). Welding automation is a means for reducing the overall cost of welding

operations by replacing some or all of the manual effort with a mechanized or automated system. Apart from reduced labor costs, automated welding also improves safety, health, and product quality. Most welding operations are hazardous due to toxic gases, noise, and electromagnetic radiation; other risks include welding in confined spaces, underwater, or in radioactive environments. Automation eliminates these risks and hazards. Also, high product quality is difficult to achieve with manual techniques. Automation can significantly improve consistency and reduce the cost of inspection and rejection.

1.1 Overview of Capacitor Discharge Welding

Capacitor Discharge Welding (CDW) is a variation of stud welding. Although it has long been in existence, this process has not been extensively used primarily due to the lack of familiarity and understanding of the metallurgy and parameters of the process. Researchers at the US Department of Energy's Albany Research Center (ALRC) have investigated the process and developed models to represent the process physics. CDW has been found to be a rapid solidification process (RSP) with great benefits in terms of metallurgy and manufacturing (Wilson, 1994).

The CDW equipment consists of a power supply, capacitor bank, and the fixtures to hold the electrodes. The process is initiated by dropping the cathode onto the anode from a pre-determined height. The capacitor bank discharges as a tip on the cathode makes contact with the anode. The tip presents a high resistance to the discharge current and is heated. It disintegrates and generates a plasma that melts the surfaces to be joined. The

actual welding process takes from 1 to 3 ms, using a current of about 10^4 A (DC). This makes the process cost effective for high volume production.

Some advantages of the process include a narrow heat affected zone, thin weld zones, on-line quality monitoring, short welding times, and high cooling rates permitting the joining of dissimilar metals. These features makes it ideal to automate the process.

1.2 Investigative Summary

Automation of CD welding operations can provide the benefits of speed and economy. Although experimental work to develop models and understand the CDW process has been done, there has not been any effort to automate the process.

In this thesis, an automated CDW system was developed and investigated. In particular, the load - unload cycle of a gravity-fed CDW unit was automated and integrated with an on-line quality monitoring system. This automation lead to improvements in cycle time without detrimental effects to weld quality. The process was applied to the joining of silver contacts to brass brackets. The welded samples were compared with similar samples made by a manual CDW process and a resistance welding process.

1.3 Thesis Organization

Chapter 2 provides a detailed description of the CDW process and a review of the literature on CDW. The literature review provides the models that have been developed for optimizing and controlling the process. A detailed description of the mechanics of the process is also described. Specific goals and objectives of this thesis are listed in Chapter 3.

Automated CDW system development is described in Chapter 4. An automation architecture is developed. Design and fabrication of the fixtures, welding head, electrical circuit, and the associated accessories is described in this chapter. Computer-based instrumentation and data acquisition is explained. A description of the machine control software, quality monitoring software, operation, and safety of the system is also provided in this chapter.

Metallographic examination results are explained in Chapter 5. An analysis of the photomicrographs of the silver-brass welds is presented. Chapter 6 summarizes the research findings, conclusions, and recommendations for future work.

2. LITERATURE REVIEW

Welding is one of the most important aspects of manufacturing operations whether it involves joining small electronic components or large structures. It is also complex, since a number of metallurgical changes occur during the process. There are a variety of welding processes, each requiring a different source of energy. Stud welding is a process for joining a metal stud (or a similar part) to a work piece. In stud arc welding, the base of the stud is joined to the other workpiece by heating the stud and the workpiece with an arc drawn between the two (AWS, 1991). If a capacitor storage bank is used to supply the arc power, it is known as capacitor discharge welding.

2.1 Capacitor Discharge Welding

In CDW, DC arc power is produced by discharging a large amount of electrical energy stored in capacitors. CDW has been used at a limited level. This is due to the lack of available process knowledge. Arc stud welding is more widely used than the CDW process (Cary, 1979). CD welding can be done in one of the following three different ways: initial contact method, drawn arc method, and initial gap method. In the initial contact method, the electrodes are first placed such that they are in contact. The circuit is then connected (electric power supplied) and the projection on the cathode presents a high resistance to the high energy and initiates the arc. The drawn arc method is complicated and uses electronic control to sequence the operation. Initially, the electrodes are in contact. When the circuit is triggered, the electrodes are separated by a small gap to draw the arc. The electrodes are then brought back together and the drawn arc produces the

heat required for the weld. In the initial gap method, there is a gap between the two electrodes with the open-circuit voltage applied. One of the electrodes is then brought into contact with the other (by gravity drop), causing a high flash of current. The initial gap method has been found to be the fastest of the three methods in terms of the actual weld time (AWS, 1991).

ALRC has conducted extensive research into this method and identified the parameters that control the process. Cylindrical geometries of CD welds were analyzed to develop models which were compared with high speed photographs of the process. It was found that CDW is a rapid solidification process (RSP) where high cooling rates (10^6 °K/s) are obtained as a result of the large weld surface areas and small weld volumes. Their analyses revealed that material is ejected as plasma from the weld area due to induced magnetic forces. Joints between dissimilar metals have been studied at ALRC. Wilson et al. (1993a) used ultra high speed photography to record the CD welding of similar metals with different tip lengths and CD welds between dissimilar metals (copper and nickel, copper and aluminum etc.). They found that CDW creates continuous metallurgical bonds between dissimilar metals with an unmixed microstructure.

2.1.1 Physical Process

CD welding requires a capacitor bank, a power supply for charging the capacitors, and fixtures to hold the electrodes. Figure 2.1 is a schematic of the CDW cycle (initial gap method). The initial position of the cathode with the welding tip and the anode is shown in Figure 2.1 (A). The dc power supply is used to charge the capacitor bank. The circuit is

open at this stage and the electrodes are separated by a distance "H" known as the drop height. After the capacitors are charged, the welding head is dropped by gravity. The electrodes come in contact (Figure 2.1 (B) shows the tip making contact); discharging the capacitance and initiating the arc. The small projection on the cathode creates a high resistance to the discharge current, causing it to heat up. The tip rapidly disintegrates and generates an arc that melts the surfaces to be joined (Figure 2.1(C)). The photographs revealed that surface layers of metal are expelled from the joint in the form of plasma and molten metal particles (Wilson et al, 1993). The arc spreads along the face of the electrodes and metal plasma moves away from the joint as shown in Figure 2.1(D). The resistance of the circuit at this instant was found to be in the order of $2 \times 10^{-3}\ \Omega$. The actual arcing time is on the order of 1 - 3 milliseconds with a current of about 10^4 amps.

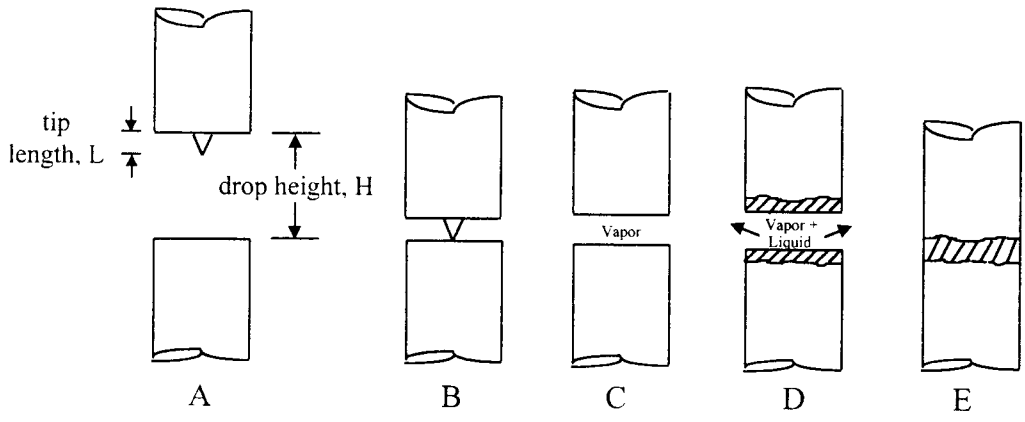


Figure 2.1 Schematic of CDW process

The super heated vapor cools and condenses into metal particles. Plasma and solid particles move away from the weld joint according to the magnetic field. A thin layer of liquid metal remains on the faying surfaces. The arc is extinguished after the electrodes

make full contact (Figure 2.1(E)), leaving a fusion zone about 0.1 mm thick (Wilson et al. 1993b).

CD welding has been successfully applied to the joining of intermetallics (Wilson et al., 1995). An analysis of CD welded Fe_3Al intermetallic alloys was performed by Wilson (1991). The electrodes used in that analysis were made of Fe_3Al intermetallic alloy cylinders with a diameter of 6.35 mm and a length of 16.5 mm. The cathode had an ignition tip with the length ranging from 0.63 to 1.4 mm. Ultra high speed photography was used to record the welds. Welding conditions that were used in the analysis are shown in Table 2.1. Equations for arc force and radius of expelled plasma were developed, but a discussion of these equations is beyond the scope of this work.

Table 2.1 Parameters used for Fe_3Al Welds (Wilson, 1991).

Voltage	90-100V DC
Capacitance	.08 F
Drop Height	50 mm
Tip length	0.63-1.4 mm

Wilson found that the welding time was controlled by tip length and drop height. The welding time (T_w) was measured from the beginning of current flow to the current rise during electrode closure. An equation to predict the welding time was developed:

$$T_w = (L+b)/\sqrt{2gH} \qquad (2.1)$$

where L is the tip length, b is the distance the electrodes melt back, and H is the drop height. Venkataraman and Devletian (1988) developed an equation for the arc power density (P) to describe the cooling rate:

$$P=CV^2/4aT_w \qquad (2.2)$$

where C = capacitance, a = area of cross-section of the weld, and V = open-circuit voltage. Welding time was found to be very important because of it's effect on the metallurgical characteristics. Welding time should be coordinated with the time to discharge the capacitors (the resistor-capacitor (RC) time constant of the circuit). Shorter welding times cause pre-solidification. Longer welding times (greater than the 2RC time constants) allow the molten metal of the electrode surfaces to solidify before joint closure. The melt back distance, b, was found to be negligible compared to the tip length. Drop height has a lesser effect on the weld time compared to the tip length since weld time was inversely proportional to the square root of the drop height.

Venkataraman and Devletian (1988) investigated CD welds for different stainless steels to find the optimum welding parameters that produce the best joint and rapid quenching rates and reported the following:

1) Weld thickness decreased with increasing drop height and decreasing ignition tip length.
2) Decreasing voltages on the capacitor also decreased weld thickness, but the voltage for good joining was 90 V (for stainless steels).
3) Drop weight did not have a significant effect.
4) Average weld thickness was proportional to arc time.

5) Ignition tip and drop height were the most effective controllers of weld arc time.

2.1.2 Process Parameter Calculations

CDW process variables are those parameters that can be adjusted to control the weld. After a CD weld joint is designed, these parameters must be estimated in order to perform the weld. The joint design provides information on the area of the weld, material, weld thickness, etc. This information has to be converted to the (electrical) energy requirements for the heat and the weld time to control the quality of the weld. Hence the primary parameters required for satisfactorily performing CD welding are voltage (V) and capacitance (C) for the energy; tip length (L) and drop height (H) for controlling the weld time.

The energy required for a CD weld is determined by calculating the thermodynamic weld energy required to melt the base metals and vaporize the ignition tip and melt-back zone. This is done by calculating the value of enthalpy required for the molten metal as well as the flash. The total enthalpy (ΔH_{total}) required for the weld is

$$\Delta H_{total} = \Delta H_{fusion} + \Delta H_{flash} \qquad (2.3)$$

where ΔH_{fusion} is the energy required for fusion i.e. for melting the base metals and ΔH_{flash} is the energy required to vaporize the tip and the melt-back zone. The mass of molten metal for each element is calculated and converted to the equivalent number of moles. The thermodynamic enthalpy values (Pankratz, 1982) for melting these metals is used to calculate the individual enthalpies and hence the total enthalpy for fusion. The energy required for flash (ΔH_{flash}) is also calculated similarly.

A correction factor of 1.5 is used to account for the efficiency of the machine due to extraneous electrical losses and the loss of energy in the form of sound and light (Wilson et al, 1995). An energy balance is made between this thermodynamic energy requirement for the weld and the energy (E) supplied by the capacitors

$$E = 1/2\ CV^2 \tag{2.4}$$

With fixed system capacitance, a value for the voltage can be determined. In an earlier study (Wilson, 1991), it was determined that the highest energy density develops at the interface when the welding time was approximately twice the (RC) time constant.

$$T_w/2 = RC = (L+b)/\sqrt{8gH} \tag{2.5}$$

Since the capacitance is fixed, equation 2.5 can be used to calculate the drop height H, and the tip length L.

The electrical schematic is shown in Figure 2.2 with the parameters of operation. A DC power supply is used for charging the capacitors to the required voltage. The DC capacitors are connected in parallel to form the capacitor bank. A detailed description of the actual circuit developed in this thesis is provided in chapter 4.

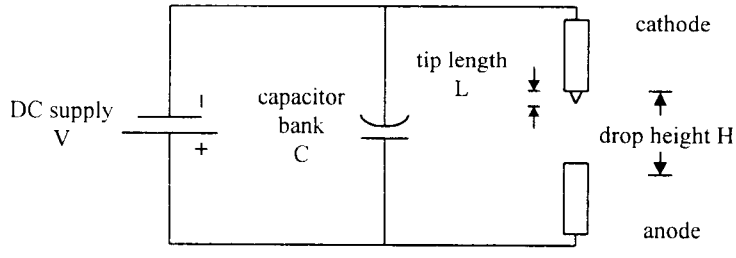


Figure 2.2 Electric schematic for CDW representing the primary process parameters

2.1.3 Rapid Solidification

Rapid solidification is the process of cooling (quenching) a material from a very high temperature. It causes the high temperature phase to be retained at the ambient temperature. Electron beam welding and laser beam welding are examples of rapid solidification processing (RSP). CDW was also found to be a rapid solidification process with a cooling rate of about 10^6 °K/s (Wilson, 1991). All these RS processes have similar characteristics like high energy density, high welding speed, etc. In electron beam welding (Cary, 1979), the parts to be welded require close tolerances as they have to be placed in a vacuum chamber. Heat is generated by high-velocity electrons in a narrow beam. The kinetic energy of the electrons is converted into heat as they strike the work piece. A major problem with this process is the possibility of the beam deflection due to stray magnetic effects. In laser beam welding (Cary, 1979), a focused high-power laser provides the heat for the weld. The beam has deep penetration power; hence it can be directed and focused precisely. This process does not require vacuum and can operate at atmospheric pressure. However, reflections can hamper the transfer of laser energy to the work piece.

The advantages of RSP are reduced grain size, increased solute solubility, and smaller heat affected zone.

2.1.4 Advantages of CDW

Because CDW is an RS process, it leads to improved solubility and stability of metastable phases. Large, brittle intermetallic phases do not have time to form in the fusion

zone interface of the joints. Because of rapid cooling rates, little porosity develops at the weld interface, resulting in a high strength joint. CD welds do not penetrate through base metals, so parts can be welded onto sealed containers. The ALRC has welded a variety of dissimilar metals using the CDW process. Joints between metals such as copper and nickel, copper and aluminum, aluminum and iron have been tested. Ordinarily, joints between dissimilar metals have to be prepared with a fluoride flux and then soldered or brazed. The fluoride flux then has to be disposed of according to environmental regulations, thus increasing the cost. CD welds do not require substantial cleaning or finishing. CDW is also an autogenous process and does not require any flux.

Since the weld time is short in CDW, the heat input to the base metal is small compared to conventional arc welding. Therefore, the weld metal fusion zone and heat affected zone (HAZ) are narrow. Distortion of the base metal is minimal. CDW allows retention of stiffness of welded parts because of the small HAZ, an extremely important feature for a satisfactory life span of parts made for contactors, circuit breakers, and relays.

In addition, the CDW process was found to have several advantages over the other RSP techniques in terms of simple equipment, parameter variation, and ease of microstructural modeling (Wilson, 1991). The process is fast and cost effective and is suitable for high production rates.

2.1.5 Limitations of CDW

CDW requires a precision arc ignition tip to initiate the welding process. The process can be only applied to electrically conductive materials. This process is generally used for cylindrical geometries with diameters in the range of 1/8 to 3/8 inches (AWS,

1991). The limitation on the size is due to the finite amount of energy stored in the capacitors and the length of the ignition tip required to spread the arc between workpieces.

2.1.6 Defects in CD welds

CDW, like any other welding process, involves many metallurgical phenomena. The weld (arc) time has a important effect on the quality of the welds. In previous studies, it was found that the optimum weld time (T_w) should equal twice the RC time constant of the circuit (Wilson, 1996, Wilson et al, 1995). Longer welding time ($T_w > 2$ RC) causes pre-solidification of the joint because the capacitors discharge before complete joining of the metals. Shorter weld times ($T_w < 2$ RC) causes a cold joint (lack of fusion) due to energy dissipation in the circuit (capacitive discharge) rather than at the weld interface.

The shape and geometry of the contact area between the surfaces also has an important effect on the quality of CD welds. The surfaces should be flat and not misaligned when they are brought into contact. A small bevel angle is required for the escape of flash (metal vapor). Surface oxides are also expelled with plasma and vapor due to the beveled geometry. Any rough spots or corrugations on the surfaces (to be joined) causes discontinuities and voids. The amount of molten metal may not be sufficient to fill the gaps between the rough spots. This could cause the entrapment of gases and creates voids. However, control of gas porosity is not required during the process as compared to some arc welding methods. CDW suppresses diffusion which could cause the formation of deleterious intermetallic phases.

Residual stresses are induced (in some metals) around the area adjacent to the weld interface. Cracks occur due to instantaneous heating and uneven cooling rates. When the thermostresses cross the yield strength of the material, cracks are formed. In very brittle materials, "underbead" cracking occurs below the weld center-line during heat-up. This is because the layer of metal adjacent to the weld center-line is subject to tension. Hot (or solidification) cracking occurs during the solidification of the weld metal. Solidification cracking also occurs due to the lack of ductility of the weld metal (Lancaster, 1993).

2.2 CDW Automation

A significant application of robots is in automated welding. The automotive industry is the largest user of welding robots (Lane, 1987). Automation has been applied to many welding and interrelated processes including brazing, soldering, and thermal cutting. Robotic arc welding operations are used in heavy industries like construction. Robots are extensively used in resistance welding operations in the automotive industry. Welding equipment is classified as manual, mechanized, or automatic depending on the level of sophistication. Some limitations (Malin, 1985) of the welding robots in existence are: expensive set-up time, changes in fixtures, finite work envelopes that limit robot positioning, tooling and software for changing parts, and the need for high investment.

The CDW process does not require complex equipment for automation. Some stud welding processes require a ferrule (a ceramic ring-shaped enclosure around the workpiece) to confine the heat generated to the weld region and limit the spread of arc. CDW does not require ferrules around the workpieces, hence the parts can be easily fed

into automated tooling and fixturing. CDW is an autogenous welding process; thus there is no need for supplying filler metal during the process. Also, since the process is applied to small parts, the equipment can be compact and portable. The CDW process does not require any complex operations like seam tracking in arc welding. Further, an automatic CDW unit is far less dangerous than other types of robotic welding equipment.

CDW has not been fully automated and implemented in a production line due to limited process knowledge. However, there have been attempts to mechanize or semi-automate the process. Erico-Jones model of a PSW-100 capacitor discharge production stud welding system is equipped with microprocessor to control the electrical circuitry. It brings the cathode into contact with the anode under the influence of gravity. It consists of a pneumatically operated semi-automatic collet clamping feature for gripping the anodes.

TRW Inc., produces the Nelson stud welder. The Nelson stud welder consists of a stud gun where the parts are loaded manually and tightened. Electronic sequencing is used to trigger the process, and after the weld, the parts are unloaded manually by spring load. An electrical controller box is used to control the voltage, interrupt the weld current etc. Neither of the above two machines have precise control of voltage, current, or any on-line process monitoring capabilities.

The Bitterman stud welder was another commercial machine developed for stud welding based on the capacitor discharge principle. In that machine, pneumatic feed is used for stroking the welding head. But fluctuation in the air pressure (stroking force) was found to have caused cold welds that resulted in poor fusion conditions.

None of the machines discussed above have automatic stud feed capability. They are either manual or semi-automatic. An operator is required to run the process. The load/unload of the parts is not automated. The operator's activities involve loading the parts into the fixtures and clamping them, operating the electrical controller, and triggering the weld. After the weld, the parts have to be manually unloaded. The CDW machine at ALRC is based on the Erico-Jones model and also uses gravity-drop for bringing the electrodes together. A high speed data acquisition system is used for monitoring the weld parameters and on-line quality monitoring of the weld.

In CDW, the actual weld time is a negligible fraction of the load-unload cycle. The manual tasks performed by the operator constitute most of the cycle time. Hence, an automated CDW system can also offer economic advantages by increasing productivity.

3. RESEARCH GOALS AND OBJECTIVES

Application of CD Welding to the joining of brass and silver electrical contacts will result in superior weld quality based on the quantity of cracks, voids and inclusions as compared to resistance welding. Also, automated CDW will demonstrate a faster process cycle time as compared to the manual CDW system with no deleterious effects to weld quality.

This research has the following five main objectives:

1. Designing a hardware system, including tooling and actuators, allowing automatic loading and welding of electrical (silver) contacts.
2. Designing a software system which controls the process automatically.
3. Integrating computer-based instrumentation and software for data acquisition and quality monitoring.
4. Conducting experimental investigation and comparison of manual system CD weld joints, automated system CD weld joints, and resistance weld joints.
5. Comparing the cycle time between the manual and automated systems.

The project has been designed to promote the implementation of an automated CD welding unit in the industry. The approach of the project has been to address the essential issues involved in the automation of CD welding.

4. SYSTEM DEVELOPMENT

This chapter describes in detail the design and construction of the various components of the automated CDW system. An overview of the system is provided first, followed by the hardware and data acquisition system. Machine control software and quality monitoring software are explained in later sections.

4.1 Background of Application

The requirements of this set up were to automate the process for CD welding silver contacts to brass electrodes (Figure 5.1). This assembly is used in 20 amp circuit breakers manufactured by Westinghouse Corporation. The contacts are the most important constituent of relays, circuit breakers, and similar electromechanical products. Their characteristics are significantly affected by material and the joint interface. Currently, they are joined by resistance welding at Westinghouse Corporation.

Resistance welding depends on the interface contact resistance. It was found that the contact resistance between silver and copper was low requiring large heat input into the joint which caused several unwanted metallurgical changes (Wilson, 1996). High heat input at the silver-copper joint caused large amounts of oxygen porosity. In addition, impurities that melt at low temperatures were produced on the weld center-line (WCL). A photomicrograph of a resistance welded joint between brass and silver is shown in Figure 4.1. The life-span of the circuit breaker was poor due to the fatigue and fracture of the metallurgical joint between the silver contact and brass bracket.

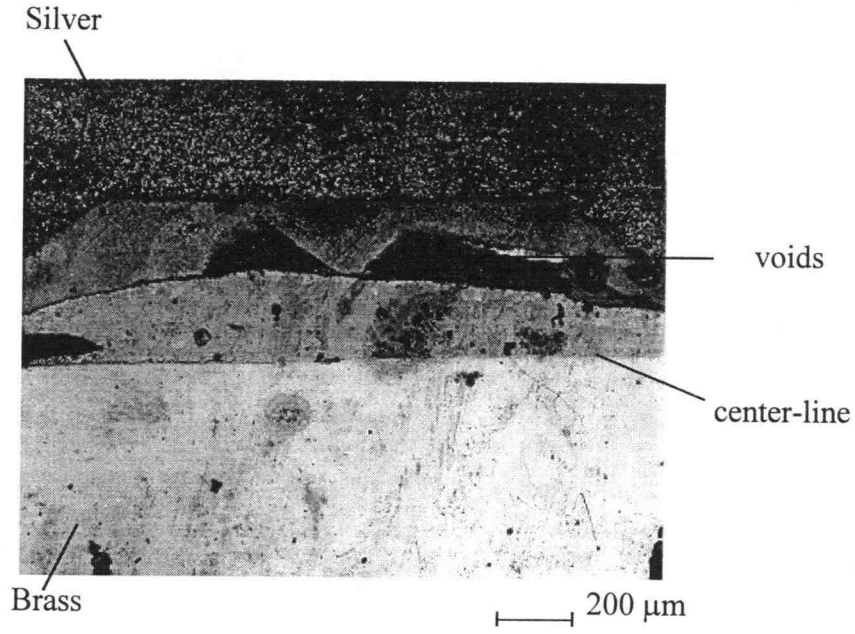


Figure 4.1 Photomicrograph of a resistance weld between silver (top) and brass (on the bottom), at a magnification of 50X.

Westinghouse Corporation has been investigating the practicality of replacing resistance welded joints with CDW joints to increase the electrical joint service reliability. Also, since a commercial automated CDW system is not currently available, Westinghouse Corporation has been interested in examining the possibility of an automated CDW system with real time process monitoring capabilities.

4.2 System Overview

The overall automation architecture for the process is shown in Figure 4.2. The machine control computer is used to control the process and the process monitoring computer is used for data acquisition and quality monitoring. A serial communications port (RS 232) on the machine control computer is used for communication with the

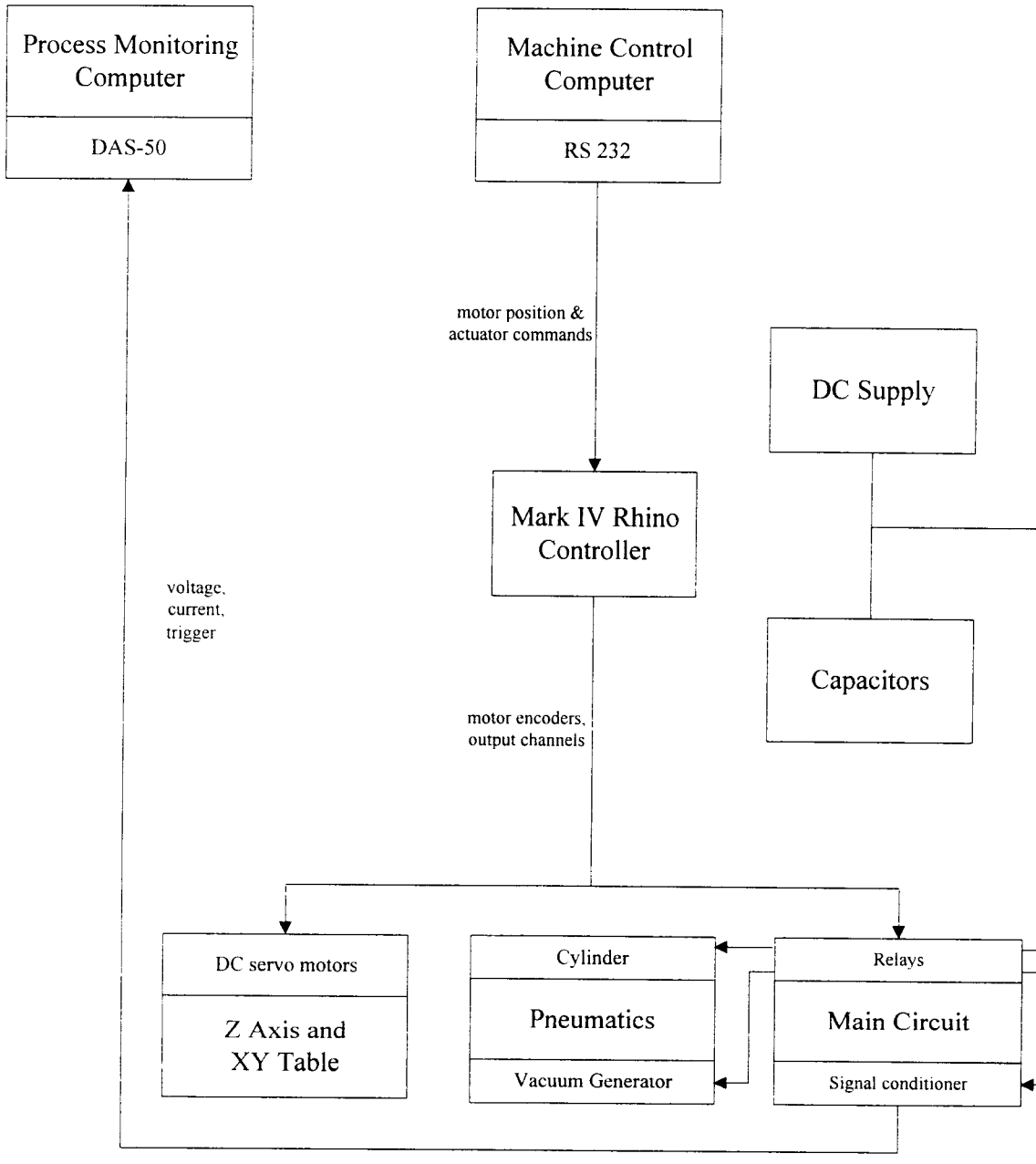


Figure 4.2 CDW Automation Architecture

controller. The hardware and equipment associated with the automation is explained in Section 4.3.

The controller is used to control the movement of the XY table, Z axis, and to interface with the actuators used to sequence the process. The controller used for this automatic CDW system is Mark IV controller (Rhino Robots, Inc.). The DC motors on the Z axis and the XY table are directly connected to the motor ports on the controller. The Mark IV unit controls the DC servomotors by sending encoder count for a required motor position. The motor circuits include automatic overload protection and stall detection features.

Output channels are provided on the controller. They are used for controlling the relays associated with the actuators. Relays were used to control the pneumatics, i.e. an air cylinder to drop the weld head and vacuum generator for button pick-up. The relay used for the air cylinder also triggers the digital pulse for the voltage and current measurement circuits. The isolation contacts between the DC supply and the capacitors are also operated by a relay. A 16-bit main processor is used for the overall operation of the system.

The controller has a built-in teach pendant used to teach motor positions and is integrated with the operation of the main controller. The teach pendant is used to teach the points of operation and is used to program the system. It operates on an 8-bit controller and has an emergency button on it to halt the whole unit if any malfunction is detected.

The DAS-50 card on the process monitoring computer is used to measure the voltage and current values during the weld. A detailed description of the computer based instrumentation and data acquisition is presented in Section 4.4. A signal conditioner is used to make the signals suitable for measurement by the DAS-50. Data collection is triggered when the welding head is released (a digital pulse is generated).

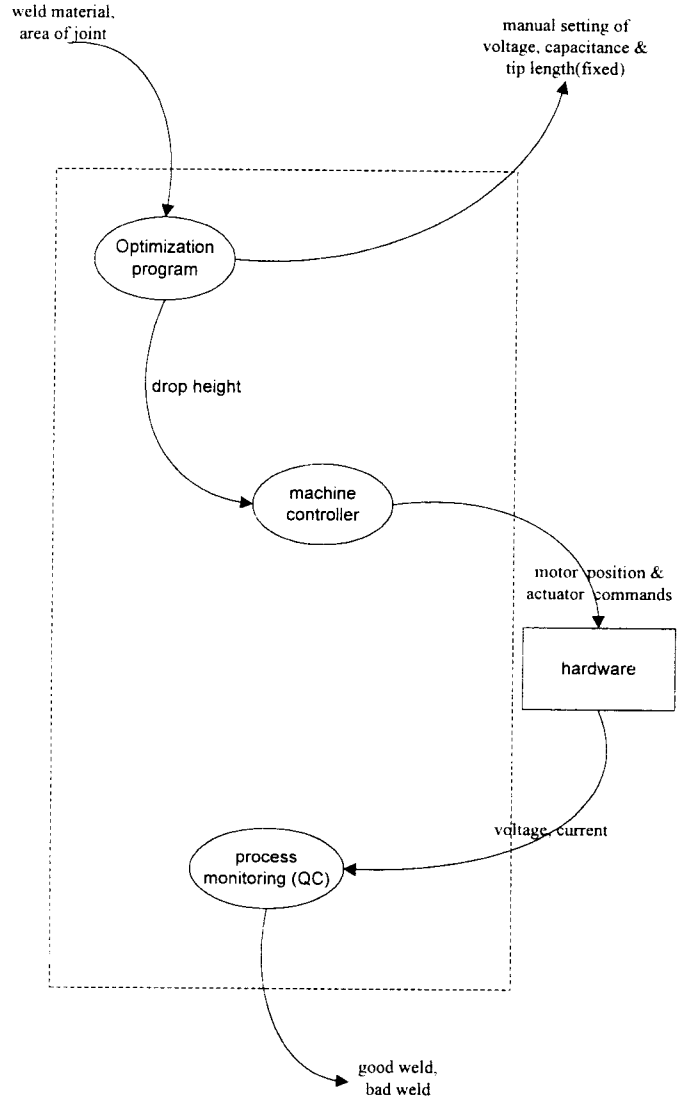


Figure 4.3 CDW Software Design

Figure 4.3 shows a structured analysis of the software design. An optimization program (under development) is used to calculate the CDW parameters for the required joint. This program essentially consists of a database of melting points and enthalpies of all the metals and performs the energy calculations as per the theory described in Section 2.1.2.

The settings of voltage and capacitance are performed manually. Control software is used to set the drop height and automate the process. This software is described in Section 4.5.1. Voltage and current during the process are measured by the data acquisition system, with the quality monitoring software is used to determine the quality of the weld based on this data.

4.3 Hardware

4.3.1 Welding Head Assembly

The welding head assembly is used to pick up a silver electrical contact and deliver it to a brass bracket for the CD weld (under the influence of gravity). It consists of the welding ram, linear bearing, and a cylinder to release the assembly so that it drops down due to gravity (Figure B2, Appendix B). The welding ram is an aluminum rod used to pick up the silver contacts.

Based on simplicity, vacuum chucking was implemented for holding the silver contacts. A chamfered cavity was milled at the end of the welding ram for the silver contact (Figure B3, Appendix B). A solenoid activated vacuum generator capable of producing up to 20 inches vacuum was used to hold the silver contact within this cavity.

The welding ram is attached to a face plate with clamps (Figure B4 and Figure B5, Appendix B). A 1/8" thick bakelite collar is used to insulate the welding ram from the clamps. The face plate and welding ram are attached to a high precision linear bearing. The linear bearing allows the ram to be dropped (upto 3 inches) onto the tip of the brass bracket. A pneumatic cylinder is used to trigger the drop of the ram assembly.

The welding head assembly is mounted on the Z axis (Figure B1, Appendix B). The Z axis unit consists of a Rhino Robots Inc. model vertical slide. It has one degree of freedom in the vertical direction and is used to move the welding head to pick up the silver button, set the drop height, and for retracting the welding ram assembly after a weld. It consists of a carriage that travels up and down on a pair of polished round bars. A DC servomotor drives the carriage through a gear and chain assembly. The DC servomotor is connected to a motor port on the Mark IV controller. Two projection brackets are used to extend the reach of the Z axis carriage (Figure B6 and Figure B7, Appendix B).

4.3.2 Fixture

A custom fixture was fabricated for the cathodes. This is a significant difference from the ALRC unit. In the ALRC unit, the brass brackets are inserted in a thin slot cut on a copper cylinder. This cylinder was then inserted in a collet chuck and tightened until the brass contact is gripped.

A matrix type fixture with cavities was designed for the brass contacts. Two rows of five cavities were machined on an aluminum block (Figure B8, Appendix B). Aluminum was chosen as compared to copper because of the ease of machining the

fixture. The brass contacts were to be inserted into these cavities. However, it was determined that there would not be positive contact between the cathode and the aluminum fixture as the parts rest freely on the fixture base. Also, any rough spot on the aluminum fixture would prevent surface contact with the brass plate. The main issue was to increase the area of contact as much as possible for good conductivity.

To address this problem, a mechanism to positively grip the parts to ensure good contact was designed. A 1/4" thick aluminum plate was machined with the matrix cavities for the brass contacts (Figure B9, Appendix B). A dove-tail rail was attached to this plate for sliding on the base fixture. After the brass contacts are placed on this plate, they are locked by sliding it on the dove tail. The sliding plate is pulled by a pneumatic cylinder. The end of the sliding plate is attached to this pneumatic cylinder and insulated by a bakelite wrapper so that the cylinder body does not conduct. This fixture, plate and pneumatic cylinder assembly are mounted on a gray PVC plate for insulation. The whole assembly is attached to the bed of the XY table.

The XY table serves as the machine bed and provides two dimensional positioning of the fixture. The XY table used is a Rhino Robots, Inc. motorized orthogonal XY table. It consists of a carriage that travels in two directions on two pairs of polished round bars. The drive in each direction is provided by a DC servomotor. A gear and chain assembly is used to transmit the drive to the carriage which slides on the polished bars. The two DC servomotors are controlled by the machine controller (Rhino Mark IV). A picture of the automated CDW system is shown in Figure 4.4.

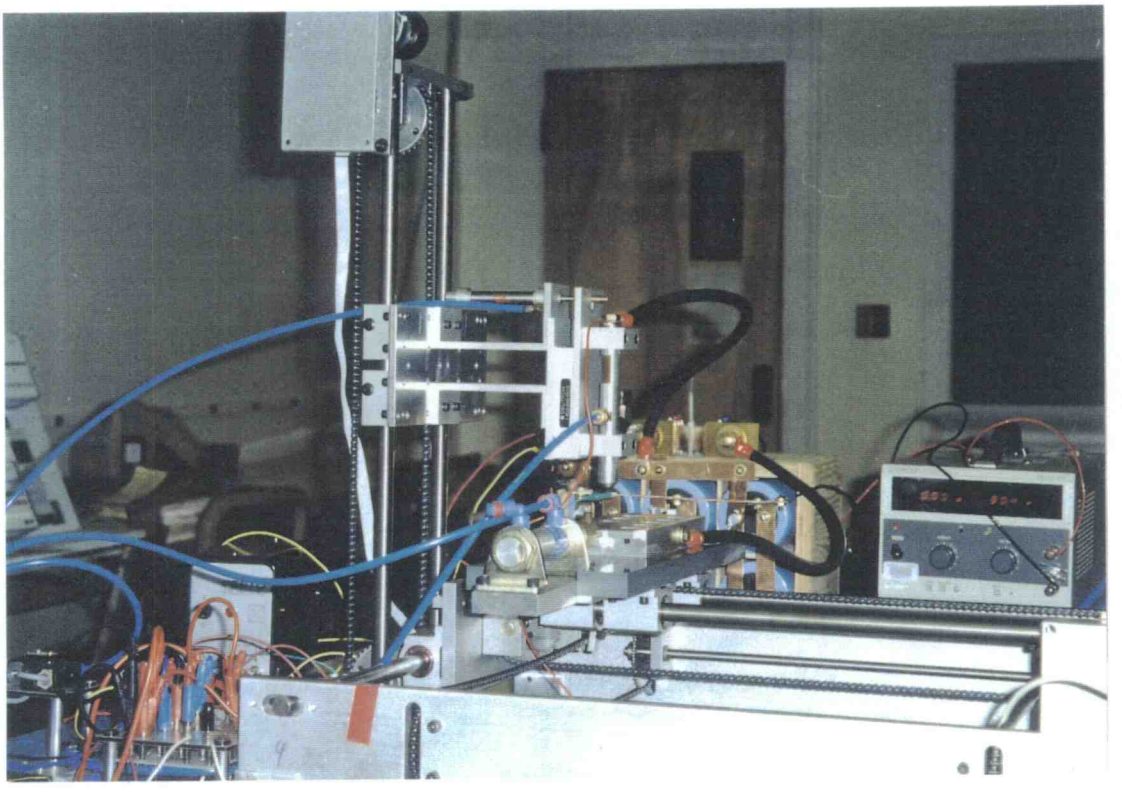


Figure 4.4 Picture of the automated CDW system.

4.3.3 Main Circuit

The main electric circuit used for CD welding is shown in Figure 4.5. The DC power supply is a special purpose supply rated for heavy duty applications. It has voltage and current control features and is capable of producing an open-circuit voltage of up to 125 volts DC. The capacitor bank consists of nine capacitors with a capacitance of .01 F each. They are mounted in a wooden box for insulation and are connected by copper bus bars. Since parallel connection was required, all the positive terminals were connected together to a common bus bar and similarly all the negative terminals to another bus bar.

Flexible cables (4 AWG copper welding cable) are used to connect the capacitor bank to the fixtures, to allow the conduction of high current that flows during the weld cycle. The anode terminal (of the capacitor bank) is directly connected to the welding ram.

The negative terminal of the capacitor bank is connected to the matrix fixture with a shunt placed in series. The shunt is used for current measurement (explained in Section 4.4.1). The length of these cables is kept to a minimum to avoid any inductive losses due to the movement and positioning of the fixtures.

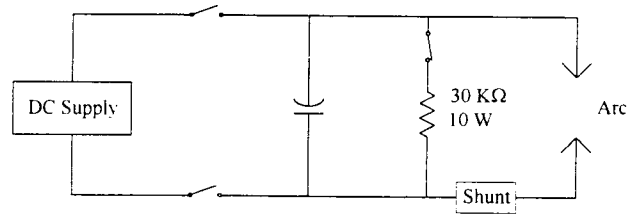


Figure 4.5 Main Circuit for CD Welding

Because capacitors have the tendency of regenerating and building up residual energy, a bleed resistor is used to discharge the energy that builds up when the machine is not operational. A 30 KΩ resistor connected in parallel to the capacitor terminals was used to drain this residual energy.

The power supply has to be isolated after the capacitors are charged to prevent any feedback from the capacitors. A double pole single throw relay is used to connect and disconnect the power supply to the capacitor bank. This also protects the power supply from the arc that is created during welding.

4.3.4 Pneumatic Circuit

The pneumatics used in the system are (1) air cylinder to release the vertical head, and (2) vacuum generator for the silver contact pick-up. Figure 4.6 represents the pneumatic circuit (ISO symbols). Compressed air (8 bar) is supplied by the air compressor. A hose is used to connect this pressure source to port 1 on the vacuum generator. The vacuum generator operates on the venturi principle and generates vacuum at port 2, which is connected to the welding ram through a hose. The vacuum generator is solenoid activated (24V DC) and is controlled by a relay through the Rhino controller.

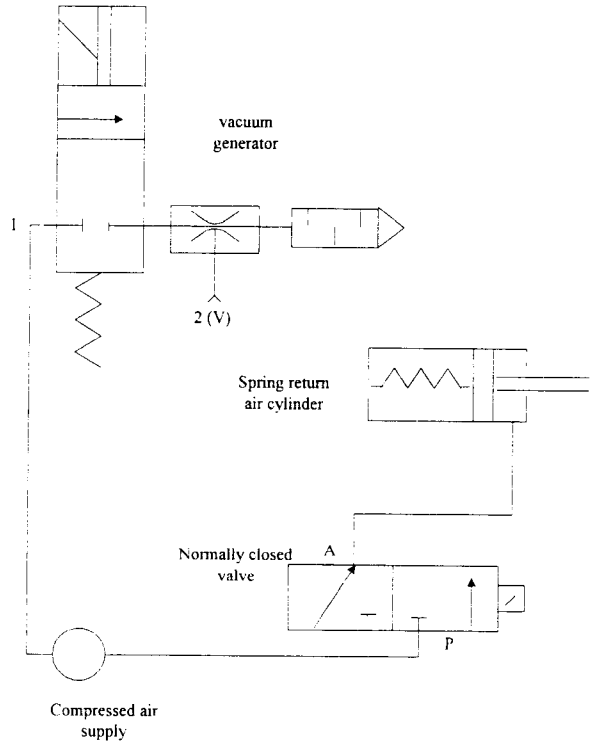


Figure 4.6 Pneumatic Circuit

Compressed air is supplied to the air cylinder through a normally closed solenoid valve. The solenoid valve also operates on 24V DC and is controlled by a relay through

the Rhino controller. The air cylinder is single-acting and has a spring return mechanism. The air cylinder is mounted on the welding head assembly and is used to release the welding ram to perform the weld.

4.4 Data Acquisition

In a manufacturing process, the outcome of operations should be within a defined range of objectives (specifications) and the process parameters must be within specified control limits. In-process measurement of varying parameters is required for analyzing the process and making corrections if deviations are present. It is also fundamental to on-line quality monitoring of the process. CD welding can be controlled by establishing the satisfactory conditions and parameters based on the theory discussed in Chapter 2. This involves weld parameter control and optimization and repeatability of the process itself. The parameter settings required for CD welding of a joint can be optimized by setting an experimental design of the parameters at different levels and testing the quality of the welds.

Computer based instrumentation was used for monitoring the CD weld parameters. CDW parameter profiles (voltage and current) are compared to determine the quality of the weld. A data acquisition system was used to acquire the data, process it to obtain the weld parameters and record the results for display and storage. The plug-in board used for this purpose is a high speed system (Keithley Metrabyte DAS-50) with 4 multiplexed analog input channels and a sampling rate of 1 MHz.

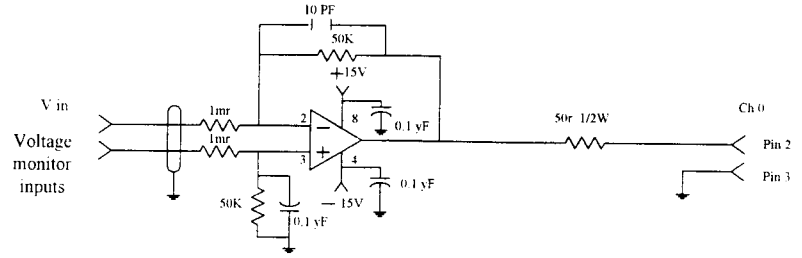
4.4.1 Signal Conditioner

The current flow during a CD weld is on the order of 6-10 kiloamperes and the voltage used to charge the capacitor bank was about 30V DC. These signals are not suitable for direct input to the DAS-50 card as it only operates within a range of ± 10V DC. Hence, the signals from the CDW process must be modified and made compatible for input to the DAS-50. A signal conditioning circuit is used to make this conversion from power signals from the process to low-power signals for the card. The signal conditioning circuitry used is shown in Figure 4.7.

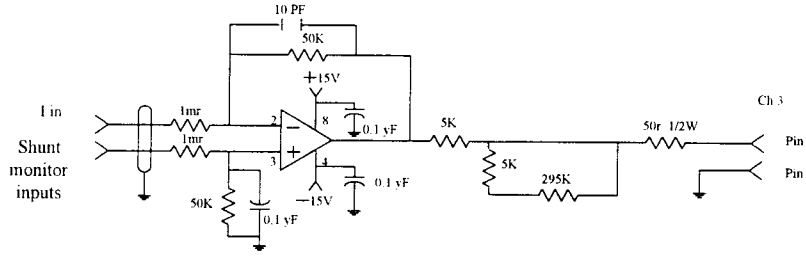
Figure 4.7(a) shows the circuit used to attenuate voltage from the process (obtained by direct connection across the electrodes). Coaxial cables are used to provide isolation and protection from electrical noise. The operational amplifier attenuates the voltage by a magnitude of approximately 20. Channel 0 of the DAS-50 card is used on the card for measuring the voltage.

Current is measured by placing a shunt in the circuit. The current shunt produces a low voltage signal proportional to the current passing through it. The shunt used in this unit produces a voltage of 50 mV for 300 amps of current in the circuit. This low power signal from the shunt is magnified by the circuit shown in Figure 4.7(b) and input to channel 3 on the DAS-50 card.

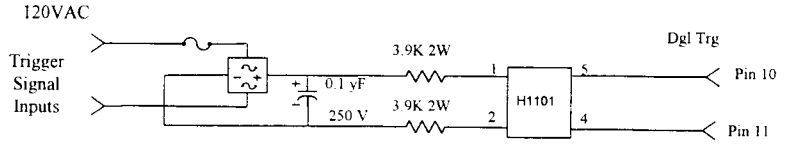
The remaining two channels (1&2) on the DAS-50 were used to obtain signals from a load cell and strobe pulses. They were used primarily for earlier research work at ALRC and are not implemented in this system. The load cell was used to calculate the



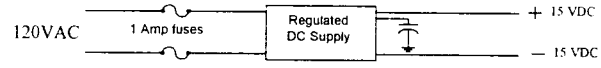
(a) Voltage measurement Circuit



(b) Current measurement Circuit



(c) Digital Pulse Generator



(d) DC power for amplifiers

Figure 4.7 Signal Conditioning Circuitry

weight required (on the vertical head assembly) to overcome the Lorentzian forces. The strobe pulse was used in high speed photography of the process.

4.4.2 Trigger

Figure 4.7(c) shows the trigger circuit used to activate the DAS-50 card to collect analog signals. When the card is set in the collection mode, it samples data and discards it until it finds the trigger. Upon finding the digital trigger, data collection is done for the required number of samples set in the software (Microsoft Quickbasic, 1990). When the vertical head is released, the relay supplies the 120V AC to this circuit. The bridge circuit rectifies the 120V AC line and generates a DC pulse which is input to the digital trigger pin on the DAS-50. Data sampling is done after the trigger (post-trigger). An opto-isolator is provided in the circuit as a protection from any stray signals.

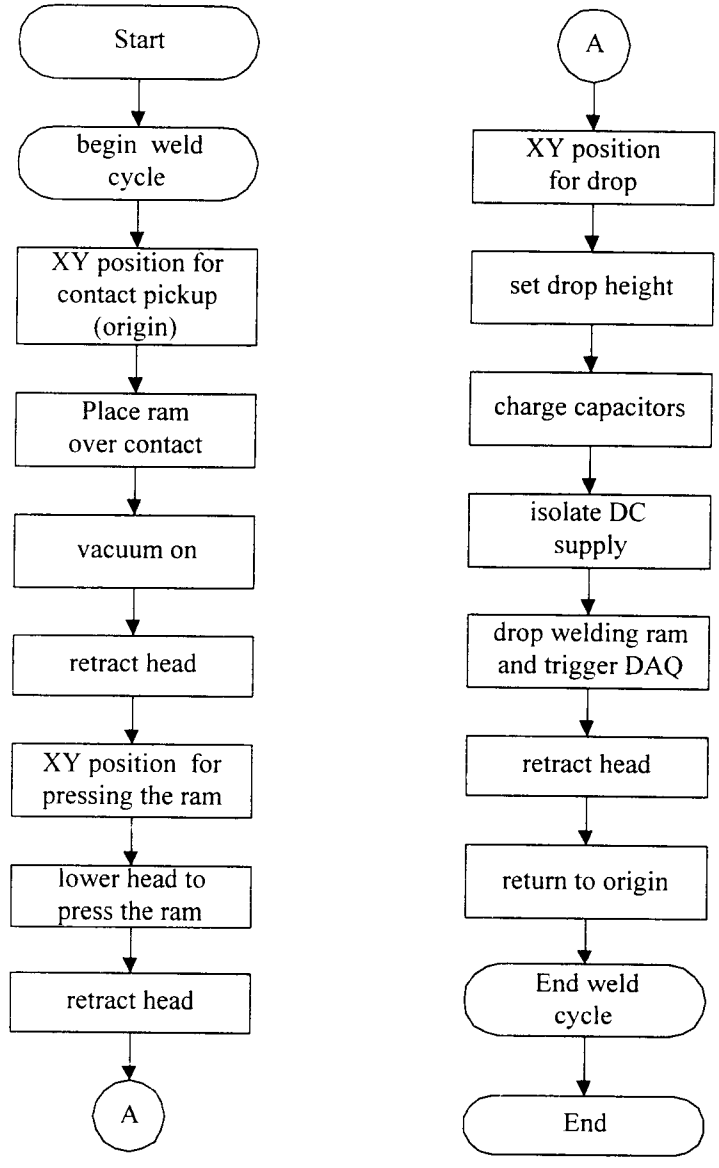
The signal conditioning circuit and the trigger circuit were built on a breadboard and assembled in a box with the ± 15V DC power supply (Figure 4.7(d)), which is used to power the operational amplifiers. Terminal strips are provided at the input and output of the circuit. A 25 pin connector is used to connect the output of the signal conditioner to the DAS-50.

4.5 Software

4.5.1 Machine Control

The machine control software is used to position the hardware and control actuators that are used to sequence the process. The software used for this purpose is

RoboTalk, a robot control language provided with the controller (Rhino Robots, 1994). The language has commands for moving motors, activating output channels, and other program control statements.



4.8 Flowchart for Machine Control Software

Figure 4.8 represents the flowchart used for the machine control software for one weld cycle. "Lead-through" programming is used to program the machine control

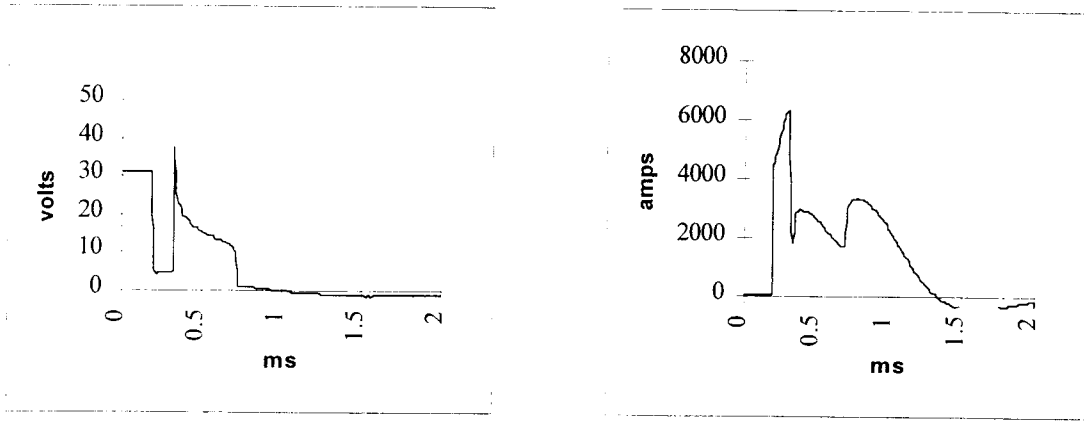
software. This consists of first moving the equipment to the required positions using the motor keys on the teach pendant. The encoder counts at the various positions are recorded and later used with the motor 'move' commands.

4.5.2 Quality Monitoring

CD welds can be examined using destructive or nondestructive testing procedures. Since the CDW process is applied to small parts, sometimes it may not be feasible to conduct tensile tests. Destructive tests do not immediately permit corrective action in production although they are valuable in research. Also, they are very expensive and time consuming. 'In-process' quality assurance procedures have been successfully implemented for other welding processes including resistance spot welding (Norrish, 1992). Optimum welding conditions are set and a test specimen is welded. The test specimen is subjected to quality tests and if found good, parameter curve profiles of this specimen are stored as a master for the application (Norrish, 1992). The curves of the production welds are then compared with the master curve profile and if there is no similarity in the profile, it is considered a bad weld.

The quality monitoring software was developed at Westinghouse Corporation (Microsoft Quickbasic, 1990). All the parameters for using the DAS-50 are set in the software. This includes the sampling rate, voltage ranges, trigger mode, channels, etc. The program activates the DAS-50 card using the digital pulse that is generated when the welding head is dropped and triggers the data collection. It then transfers 200 values of current and voltage data in steps of 10 microseconds to the computer's memory. The 200 values of voltage and current are stored in arrays and are plotted against time. Figure 4.9

illustrates graphs of voltage and current against time from a sample CD weld between a silver contact and brass bracket. The values are also stored in a data file which can be used for experimental investigation. The voltage and current profiles are then compared, and if there is no match a "bad weld" label is displayed on the screen.

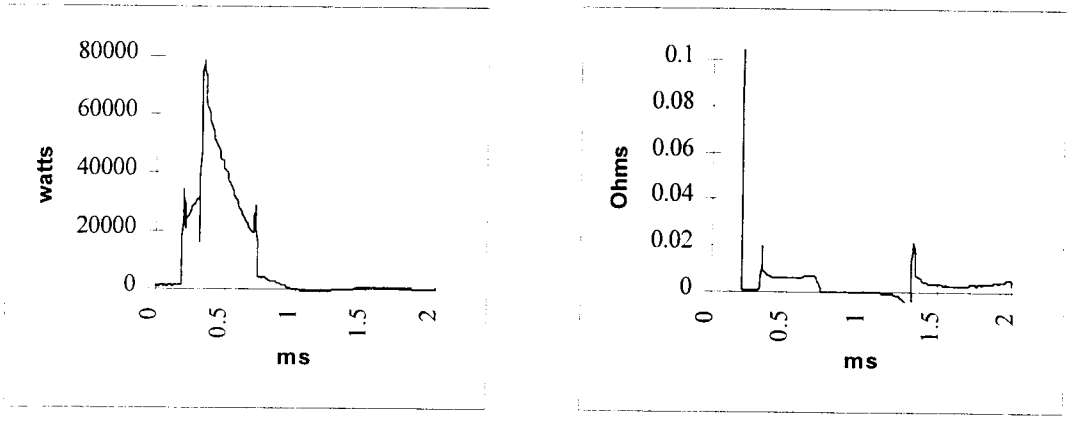


(a) (b)

Figure 4.9 Plots of (a) voltage vs. time and (b) current vs. time for a CD weld

The welding time starts when the current changes from 0 and the cathode tip comes in contact with the anode. This marks the beginning of the weld time (t_b). Current rapidly spikes to a maximum value when contact is made (Figure 4.9(b)). The arc causes the discharge of energy and the tip starts melting. The current drops down due to a change in the resistance of the circuit. After the tip melts and the joint is made, there is an increase in the current flow due to an increase in the area of contact. The current through the circuit diminishes to 0 after the capacitors are discharged. This marks the end of the weld time (t_e). The time between t_b and t_e gives the actual weld time.

From the voltage and current data, resistance and power are calculated. These curves are shown in Figure 4.10. From the dynamic resistance curve, a fluctuation in the resistance is observed as the tip makes contact (arc begins). During arcing, it remains relatively constant.



(a) (b)

Figure 4.10 Plots of (a) power vs. time and (b) resistance vs. time

The total weld energy is calculated by finding the area under the power curve between t_b and t_e or by using numerical integration.

$$\text{Total energy for weld} = \int_{t_b}^{t_e} P\,dt \text{ watts.} \qquad (4.1)$$

The weld energy calculated from equation 4.1 can be used to verify if enough energy was developed at the joint interface.

4.6 Operation

The first step involves switching on power (120 v ac) to the main DC supply, signal conditioner, and other DC supplies (associated with actuators). The required voltage and capacitance is set manually. A detailed list of operating instructions is

provided in Appendix A. Robotalk software is loaded and the machine control software file is executed. The welding head picks up the silver button from a fixed position on the XY table and moves to the position for weld. The capacitors are charged and the DC supply is isolated. The weld is performed by triggering the air cylinder. The welding head is then retracted up and the XY table returns to the origin.

4.7 Safety

Safety is an important consideration of CD welding. Although potential hazards are minimized by this automated CDW unit, some precautions are still necessary. Unlike conventional arc welding and gas welding, there is no metal splatter or release of toxic gases in CDW. However, CDW involves very high currents and capacitance and good electrical safety must be provided.

The automated CDW equipment was installed in a clean and dry area, adequately guarded from moisture. Power cables and terminals were shielded from accidental contact by personnel or metal objects. The frame and electrical circuitry were connected to good electrical ground. All the electrical connections are tight. Insulation was provided between the fixture and the XY table and similarly between the welding ram and vertical head assembly. All the equipment including cables, wires, and fuses were used within their current and duty cycles.

At the end of the weld cycle, the circuit is disconnected. Residual and excess voltage is drained by the bleed resistor. An emergency button on the control pendant is used to stop the machine if a malfunction is detected.

5. EXPERIMENTATION AND RESULTS

5.1 Experimental Set-up

The automated CDW system was set-up to weld silver contacts to brass. The contacts are made by compacting silver powders and sintering them to form a disk of 1.47 mm thickness and 3.91 mm diameter. It has a face centered cubic (FCC) crystal structure. The actual composition is 82% silver, 11% tungsten, 2.9% nickel, and negligible amounts of other elements. One side of it has corrugations for obtaining a high resistance for the required heat when used in the resistance welding process. The brass conductor is a β-phase mixture of Copper and Zinc. It has a body-centered cubic (BCC) crystal structure. The commercial name for this brass is yellow brass (ASTM B13437). It has a .508 mm ignition tip. The front and side views of these parts are shown in Figure 5.1.

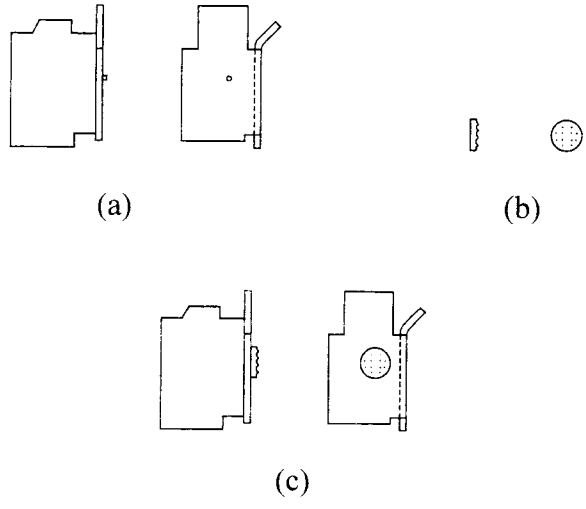


Figure 5.1 Front and Side views of (a) brass bracket
(b) silver contact, and (c) welded assembly

The welding parameters and energy requirements were made for a weld thickness of 100μm with a flash of .01 grams. These calculations were done according to the procedure described in section 2.1.2. The parameters used are given in the table below.

Table 5.1 Parameters used in the experiment.

Voltage	20-35 V DC
Capacitance	.09 F
Drop Height	12.5 - 25.4 mm
Tip length	.508 mm

5.2 Results

CD welds were made on the manual machine (at ALRC) and on the automated system using the parameters given in Table 5.1. Metallographic examination was done to compare the welds between the automated unit and the manual unit as well as with resistance welding. A cycle time comparison between the two machines was performed.

5.2.1 Specimen Preparation

Transverse cross-sections of the joints were used for metallographic investigation. A water-cooled aluminum oxide abrasive wheel was used to section all specimens. Ample cooling was provided during cutting to minimize the heat input and any alteration to the original structure of the specimen (Kehl, 1949). Since the specimen were too small to be handled conveniently, they had to be appropriately mounted to facilitate the investigation.

A thermosetting plastic (bakelite) was used to mount the specimen. Green bakelite molding powder was used to make the mounts of uniform size (1 inch diameter and 3/4 inch length). A Buehler mounting press was used to apply heat and pressure simultaneously. The specimen was placed on the bottom of a greased crucible and bakelite was poured over the specimen. This was then compressed on the press using a pressure of 8000 psi and a temperature of about 150°C. After a short curing time, it was cooled down to about 90°C and the specimen was ejected from the molding die.

The next step was to obtain a flat, semi-polished surface of the specimen. This was done by grinding the specimen on a series of abrasive grinding laps. Rough, intermediate and fine grinding was done using silicon carbide grinding laps of increasing grit size. A Leco automatic polisher was used for this procedure. The samples were mounted on a cartridge holder.

Circular-cut silicon carbide paper was attached to the disk. The disk was then rotated with the holder resting on it. A constant load of 10 lb. was applied. Excessive pressure was not applied to avoid deep scratches or the formation of disturbed metal. The specimen was kept cool by a water spray. Grinding was done for about 2 minutes. The holder was then removed and was cleaned in an ultrasonic cleaner to remove any abrasive particles present on the holder or the specimen. The specimen were then observed for scratches using a magnifying glass. This procedure was repeated with increasing grit sizes for intermediate and fine grinding. Four sets were performed using grit sizes of 120, 240, 320, 400, and 600.

Similar procedure was used for polishing the specimen with diamond dust as the abrasive. Intermediate and fine polishing was done with particles sizes ranging from 6-0.25 microns.

All the specimens were photographed to a magnification of 50X and 200X using a Bausch & Lomb Research II Metallograph. This optical examination was used to determine the presence of voids, inclusions, and to compare the welds made using the manual and automatic machine.

5.2.2 Analysis of Results

5.2.2.1 Resistance Welding vs. Manual CD Welder

In resistance welding, the heat required for welding is generated by the resistance to the flow of current through the parts to be joined. A pair of electrodes (one on either side of the parts to be joined) conduct the electrical current through the joint interface. The brass and silver contacts are currently resistance welded at Westinghouse with 20 volts AC and a current on the order of 100 - 200 amps. A photomicrograph of a sample weld is shown in Figure 5.2. Several unwanted metallurgical defects can be observed near the weld center-line (WCL).

Resistance welding depends on the interface contact resistance. It was found that the interface contact resistance between silver and copper is low (Wilson, 1996) which required a large heat input into the joint. Since the resistance at the joint interface is low, the heat needed to make the weld develops at the electrode interface and flows to the cold joint through the silver contact and then through copper (brass bracket). The parts are

over-heated and the large heat input into the joint caused large amounts of oxygen porosity.

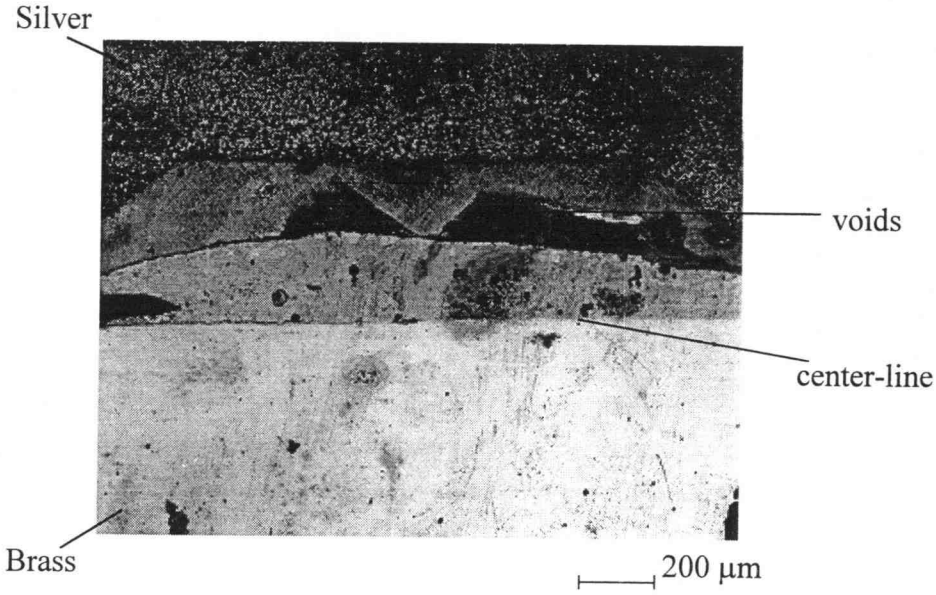
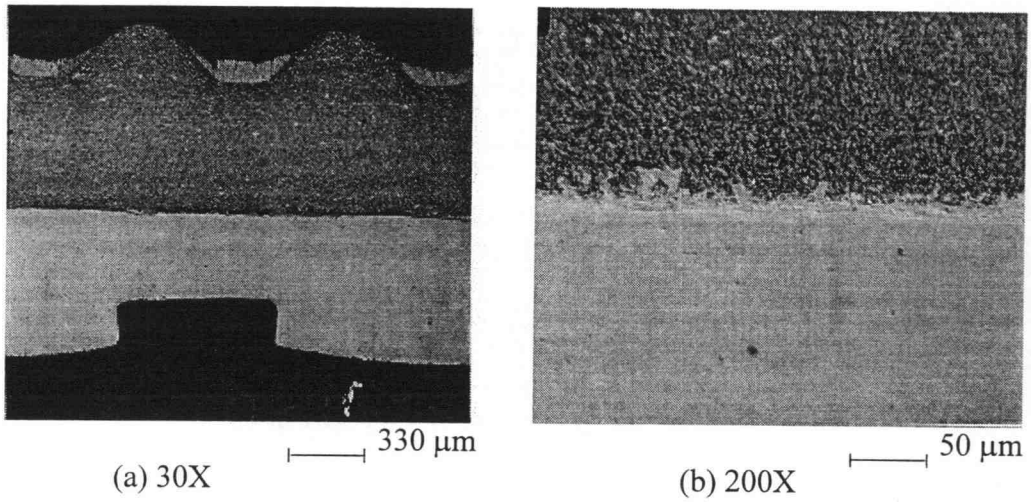


Figure 5.2 Photomicrograph of a resistance weld between silver (top) and brass (on the bottom), at a magnification of 50X.

Because of the extreme mechanical load requirements, the brass brackets required high modulus of elasticity and strength. These materials are hardened and strengthened by cold rolling. High heat input (due to resistance welding) anneals the base metal and reduces the yield strength in cold rolled copper. In addition, low melting impurities were produced near the WCL. The diffusion of Zinc is also noticed at the interface.

On the manual CD welder at ALRC, the silver contact was welded to the brass part with the flat side being welded. Photomicrographs of a sample weld done at optimum conditions are shown Figure 5.3. The weld centerline is free of voids and inclusions.



(a) 30X (b) 200X

Figure 5.3 Photomicrographs of a CD weld performed on the manual machine with the flat side of the silver contact (top) welded to brass (bottom)

Continuous bonds are created because silver and copper readily form a solid solution as they have the same valence and a small difference in the atomic radii and electronegativity. No oxide layers can be seen. It can be observed that copper has infiltrated into the surface of the Ag-W alloy, forming an unmixed zone (commonly referred to as "marble cake" structure).

5.2.2.2 Automatic CDW System vs. Manual CD Welder

Sample welds were initially performed with the corrugated side of the Silver contact touching the welding ram. The suction hole that was drilled on the welding ram further reduced the area of contact between the welding ram and the corrugated side of the silver contact. Due to insufficient contact, there was a capacitive discharge and the silver contact was fused to the welding ram. To address this problem, CD welds were performed with the corrugated side of the silver contact being welded to the brass bracket.

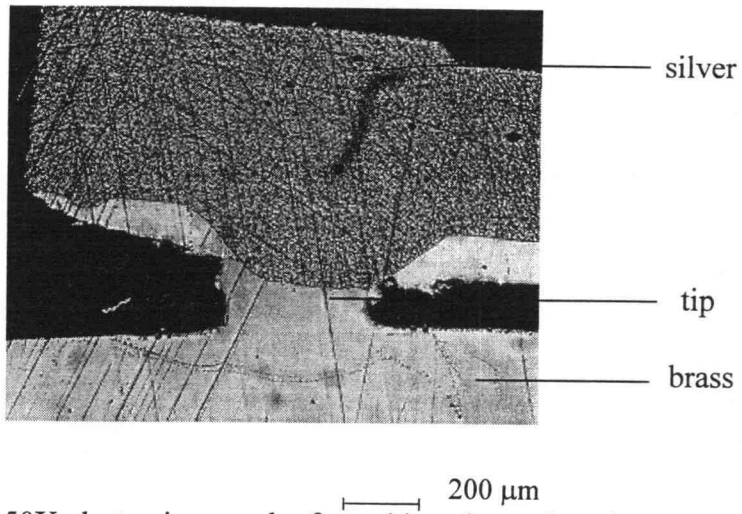


Figure 5.4 50X photomicrograph of a weld performed on the automated system V = 20V, H = 18 mm, C=.09 F

Figure 5.4 shows a weld performed at low voltage on the automated unit. Low energy density fails to create sufficient arc power between the electrodes. Due to insufficient arcing, the tip did not completely vaporize.

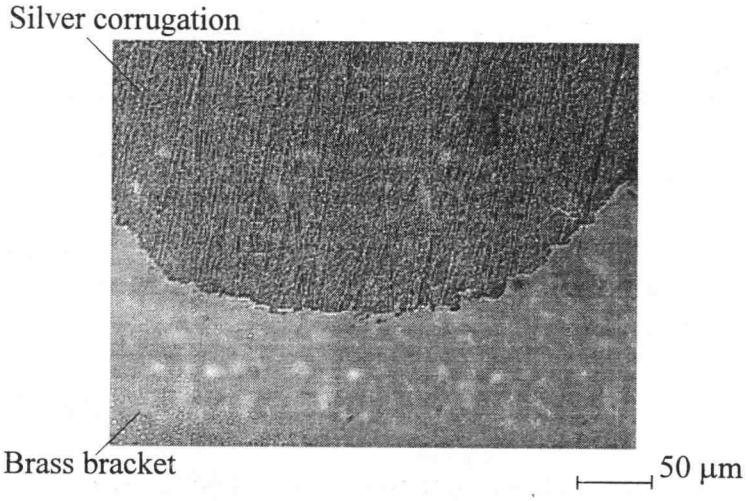


Figure 5.5 A 200X photomicrograph of a CD weld performed on the automated system, at optimal parameters V = 31V, H = 25 mm, C = .09 F

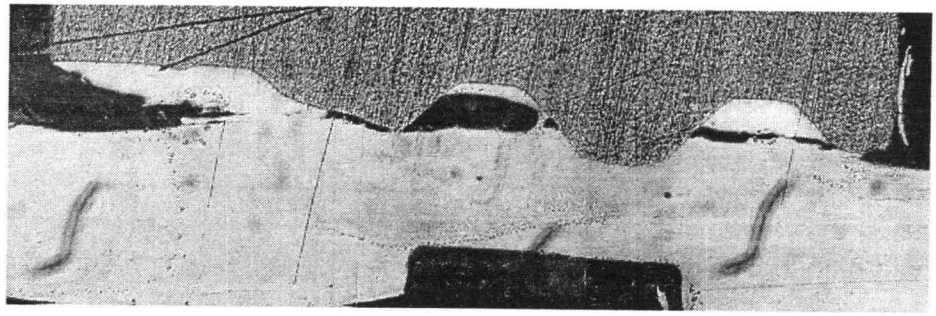
A 200X photomicrograph of a CD weld made at optimum conditions (V = 31.5V, C=.09F, H=25mm, L=.508mm) on the automated system is shown in Figure 5.5. A corrugation on the silver button was continuously welded to brass. No cracks, voids, or inclusions were observed. The joint is thin and is less than 10μm wide. These optimal parameters for CD welding silver contacts to brass were determined in an earlier study (Wilson, 1996).

The voltage was gradually increased in steps of 3 volts. Higher voltages caused longer arcing time and more flash. Photomicrographs across the entire weld interface are shown in Figure 5.6. Higher energy densities (high heat inputs) also created welds of same thickness as of low heat input welds. It appears that the extra energy was used in forming flash and did not increase the weld thickness or the width of the HAZ.

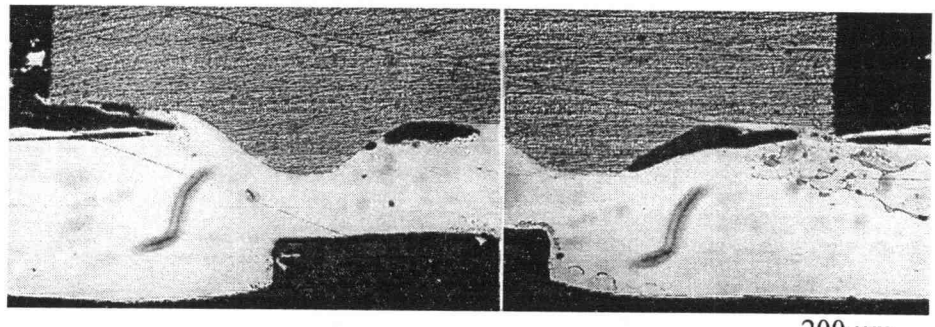
Continuous joints can be observed between silver corrugations and brass in both the welds. However, some voids are present in both the welds. This is due to the corrugated side of the silver contact being welded to the brass bracket. The quantity of molten metal was not sufficient to fill the spaces between the corrugations. Some gas porosity can be observed due to the entrapment of oxygen from the disassociation of surface oxides.

In Figure 5.6 (a), it appears like the silver contact is misaligned. Measurement of the angle between the brass bracket and the base of the silver corrugation revealed that there is a small difference between the misalignment in the automated and manual weld (0.23° and 0.7° respectively). A careful examination of the photomicrograph of the automated weld (Figure 5.6(a)) reveals that the silver contact was not centered on the tip

of the brass bracket. This caused a lever-arm effect on the silver button resulting in the momentary misalignment of the faying surfaces. This resulted in an uneven discharge across the surfaces. This is evidenced as more metal has been removed from the corrugation on the left of the photomicrograph. The uneven discharge resulted in less efficient use of arc power and, consequently, less penetration of the button into the bracket.



(a) automated



(b) manual

Figure 5.6 Photomicrograph showing the entire weld interface. The silver contact is on the top and the brass bracket is on the bottom.

The weld area obtained with the corrugated side of the silver contact is the area of the corrugations remaining after the metal vapor (flash) has escaped. The theoretical and

actual weld area calculations are provided in Appendix C2. Weld areas obtained with the automated and manual systems were also calculated empirically. This was done by measuring the distance 'd' from the base of the corrugations to the brass surface. These values are provided in Table 5.2 and 5.3.

The value of h (the thickness of spherical segment evaporated in the form of flash) is the difference between the radius of the corrugation and the distance d (Appendix C2). The empirical weld areas are calculated using equation C2.4 and C2.7 (see Appendix C2).

Table 5.2 Distance from base of Ag corrugation to brass surface of the Automated Weld (See Figure 5.6(a))

No.	d cm
1	0.0320
2	0.0254
3	0.0193
4	0.0178
Avg. d	0.023

Table 5.3 Distance from base of Ag corrugation to brass surface of the Manual Weld (See Figure 5.6(b))

No.	d cm
1	0.0193
2	0.0127
3	0.0101
4	0.0101
Avg. d	0.0131

The empirical and theoretical weld areas obtained are provided in Table 5.4. The empirical weld area obtained from the manual unit was larger than that obtained from the automated CDW system. This is because of the uneven discharge across the automated weld (see explanation of Figure 5.6(a) earlier in this section). The uneven discharge is due to poor XY positioning in the automated system. Overall, the weld area of the automated system is within the range of the theoretical calculations. This suggests that an explanation other than weld pick-up misalignment is needed to explain the differences in weld area. A plausible explanation is that the manual unit is more energy efficient than the automated unit. This is consistent with observations of discharging (and thus loss of efficiency) both in the welding head and anode fixture of the automated system.

Table 5.4. Empirical and Theoretical weld area comparison between automated and manual system

	avg. d cm	h cm (0.038-d)	V cm^3	a cm	weld area from all 12 corrugations, cm^2
Automated	0.023	0.015	2.3×10^{-5}	0.03	0.034
Manual	0.013	0.025	5.8×10^{-5}	0.035	0.048
based on theoretical mass expelled	___	0.02	3.97×10^{-5}	0.033	0.041
based on actual mass expelled	___	0.015	2.3×10^{-5}	0.03	0.034

5.2.2.3 Cycle Time Comparison

Cycle time comparison between the automated CDW system and the manual CDW unit was performed. The total cycle time for performing a weld is the time from the

loading of the components to the unloading of the finished assembly. The set-up operations in both the machines include setting the values of voltage and capacitance required for the weld. The welders activities in a weld cycle on the manual unit are: loading the parts into the fixtures, setting the drop height, operating the electrical controls (power on, remove bleed resistor, charge capacitors, isolate the power supply), triggering the release of welding head to perform the weld, removing the assembly, and resetting the electrical controller. In the automated CDW system, after the brass bracket is inserted into the fixture and the silver contact is place at the pick-up point, the machine control software has to be executed.

Table 5.5 Cycle time comparison between automated and manual system

	Cycle Time (sec)		
	weld 1	weld 2	Average
Manual	119	123	121
Automated	27	27	27

Cycle times for performing two consecutive welds were measured on both the machines. The cycle time on the manual unit was measured when it was operated by a semi-skilled worker. The cycle time comparison is provided in Table 5.5. The automated CDW system has a superior cycle time and is approximately 4.5 (121/27) times faster than the manual unit.

5.3 Issues and Limitations of the Automated CDW System

The welding head is the most critical design in the development of the automated CDW system. Automation of loading the silver contact, welding it to the brass bracket,

and unloading the (joined) assembly were the core functions of the unit. To perform these functions, the two most important design requirements of the head were: (i) to pick up the silver contact in a good orientation, and (ii) to provide maximum surface area of contact between the ram and the button for the conduction of high current during the weld.

The first criteria, i.e. the pick-up of the silver contact required the accurate positioning of the welding ram above the silver contact. This was dependent on the tip of the ram and the accuracy of the XY table. Figure 5.7 shows a misaligned pick up of the silver contact due to positioning error.

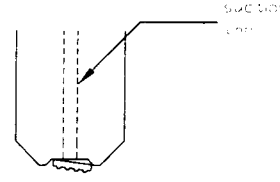


Figure 5.7 Misaligned pick-up of the silver contact

The repeatability of the XY table was approximately 1 mm. To account for this repeatability, a chamfer was provided at the end of the welding ram. The welding ram was programmed to press against a flat surface which caused the silver contact to be forced into the cavity of the welding ram.

The second design criteria was the area of contact between the welding ram and the silver electrode. Insufficient area of contact between the welding ram and the silver contact causes a (capacitive) discharge at the interface, thus joining the silver contact to the ram. Since vacuum chucking was implemented for pick-up, a suction hole was drilled through the welding ram. Analysis of the (vacuum) gripping force and the hole diameter

is provided in Appendix C1. This analysis shows that a smaller diameter hole will still provide enough suction for the contact while increasing the contact area between the silver contact and the ram.

Flash (metal vapor) that is formed during the weld deposits on the tip of the welding ram. Over a period of time, this accumulates to form a thin layer and increases the resistance between the welding ram and the silver contact. The high resistance could cause loss of energy at this interface and fuse the silver contact to the weld ram. Therefore, the welding ram has to be maintained properly and the accumulated flash should be removed. The tip of the welding ram can also be made insertable to address this problem.

Also, the feeding of silver contacts and the brass brackets has not been automated in this unit. The silver contact is manually positioned at a fixed point on the XY table and the brass bracket is loaded into the fixture manually. An automatic escapement / feeder mechanism can be designed for implementing the automated CDW system on a high volume production basis.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Since the actual process time in CDW is very small, the speed and accuracy of the system depends on the speed of the positioners and actuators. The time taken for one complete weld cycle on the automated CDW system was approximately 4.5 times faster than for a weld cycle on the manual unit.

CD welds between brass and silver were found to be superior to resistance welds. An unmixed microstructure of the cathode and anode materials was observed without any cracks, voids or inclusions. There was no significant difference in the metallurgical characteristics of the welds made by the manual unit and the automated system. However, better weld areas were obtained with the manual unit. Because clamping force (in both the welding ram and the fixture) is not great in the automated system, the automated system is not very energy efficient. Future methods of automated loading / unloading should take this into consideration.

6.2 Recommendations

A system of higher speed and accuracy can shorten the process (cycle time). Positioners of higher speed and greater accuracy controlled by a sophisticated machine controller can be used to make a production machine. The tooling and fixtures that were designed were for specifically handling the brass brackets and silver contacts. The tooling and fixtures can be made modular and flexible to weld parts of differing geometry's and sizes. Also, copper tooling and fixtures can enhance the quality of welds made by the

automated system. Semi-automatic parts feeding was used in the set-up. The feeding of parts and unloading of the assembly can be fully automated.

The welding head developed was a gravity feed unit. With the gravity feed unit, the weld time can be calculated easily. Pneumatic and spring feed mechanisms are used in other stud welders (Bitterman, Nelson etc.). DC motor-powered ramming of the welding head has never been implemented. Powered feed of the electrodes can be investigated for it's speed as well as it's impact on the weld time and the metallurgy.

The optimization program described in Section 4.2 has not been implemented in this system. The optimization program is essentially a database that consists of the melting points, thermodynamic enthalpy values of the metals. When the weld design information (area of cross section, material etc.) is input to this program it automatically generates the process parameters required (V,C,L,H) for the weld.

Also, since classical feedback control cannot be applied to CDW, the machine controller can be programmed to analyze the data obtained from the data acquisition system and make on-line adjustment of variable parameters like drop height and voltage setting. This can be done by a custom data acquisition software or by an appropriate algorithm (e.g. Neural Network) that is capable of estimating the deviation and propagating the error. A Neural Network program was developed at Eaton-Westinghouse corporation to backward-propagate the deviation of the CD weld parameters.

In conclusion, this automated CDW system has provided a foundation for conducting further investigations, especially in the level of automation and control of the CDW process.

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APPENDICES

APPENDIX A
AUTOMATED CDW SYSTEM OPERATION

Before operating the system, a visual examination of the unit is required to check for any loose wires, unprotected cables, etc., for safety purposes. Operation of the unit is explained in the following steps:

1. Set the required capacitance on the capacitor bank. This is done by connecting the required number of copper bus bars of the positive terminals of the capacitors. Each capacitor is rated for 10,000 μF. Since there are nine capacitors, the maximum capacitance that can be obtained is 90,000 μF (.09 F). Disconnect the bleed resistor using the toggle switch.
2. Turn on the power (120v AC) to the Kenwood dc power supply, signal conditioner, Rhino controller, and the two dc power supplies that are used for the relays and actuators.
3. Set the required voltage (for the weld) on the Kenwood power supply using the voltage control knob. A digital display of the voltage is provided on the front panel of the power supply. This set voltage is then obtained at the terminals by pressing a push button on the front panel.
4. Switch on the air compressor. The air compressor automatically stops after the pressure builds up to 8 bar.
5. The quality monitoring software is then executed typing "weldgaf" on the process monitoring computer. Robotalk software is loaded on the machine control computer by typing "rt" and pressing enter until the menu of the software appears on the screen. The machine control program "autocdw" is loaded.

6. Place the silver contact on the small cavity milled on the fixture assembly and insert a brass bracket into the fixture. The valve on the manifold of the compressed air line is opened and the machine control program (autocdw) is executed to perform a CD weld.

Steps 1-5 are the set-up operations required before performing the weld. To repeat the process step 6 has to be performed.

APPENDIX B
MECHANICAL ASSEMBLY AND COMPONENT DRAWINGS

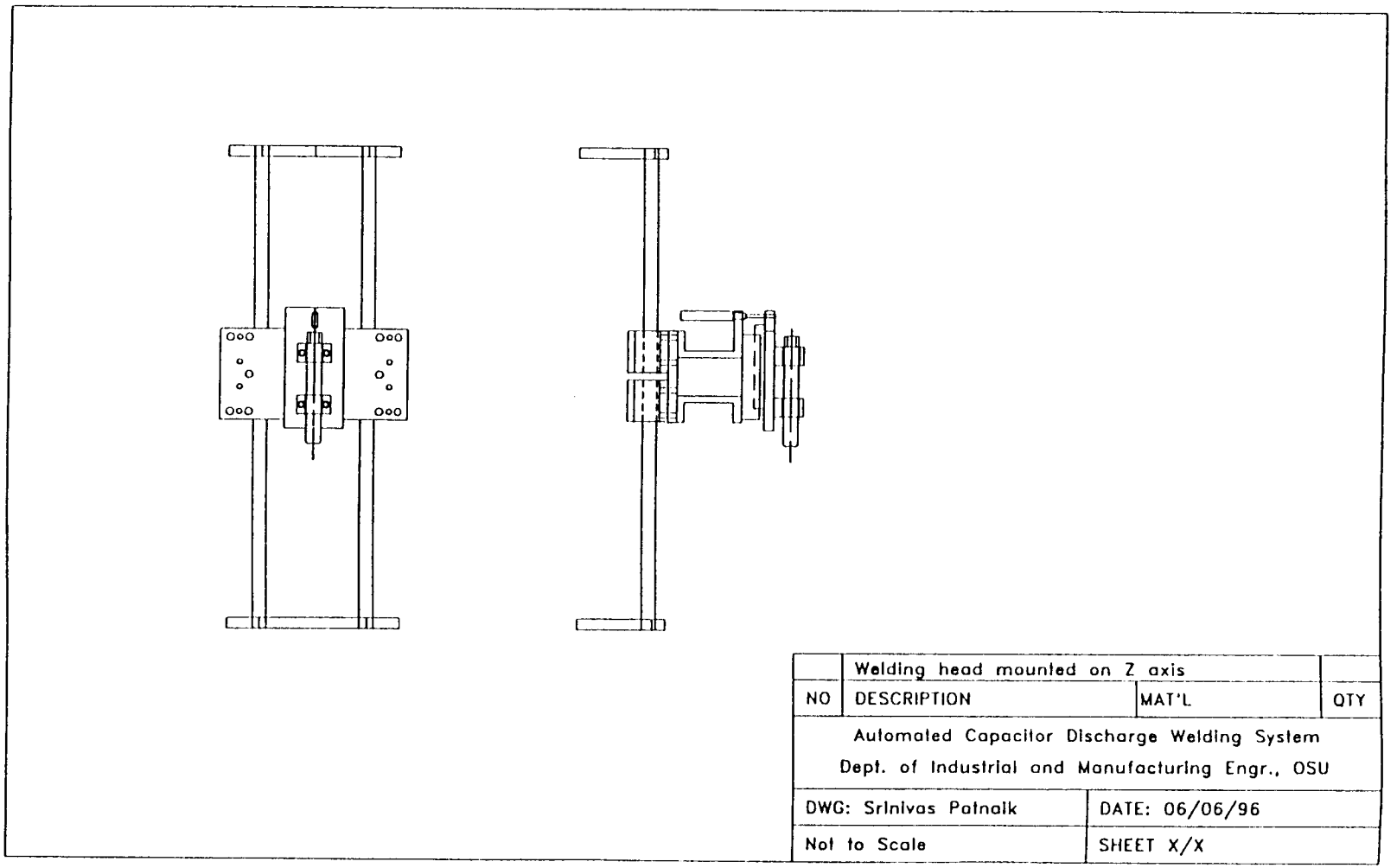

Figure B1 Welding head assembly mounted on Z-axis

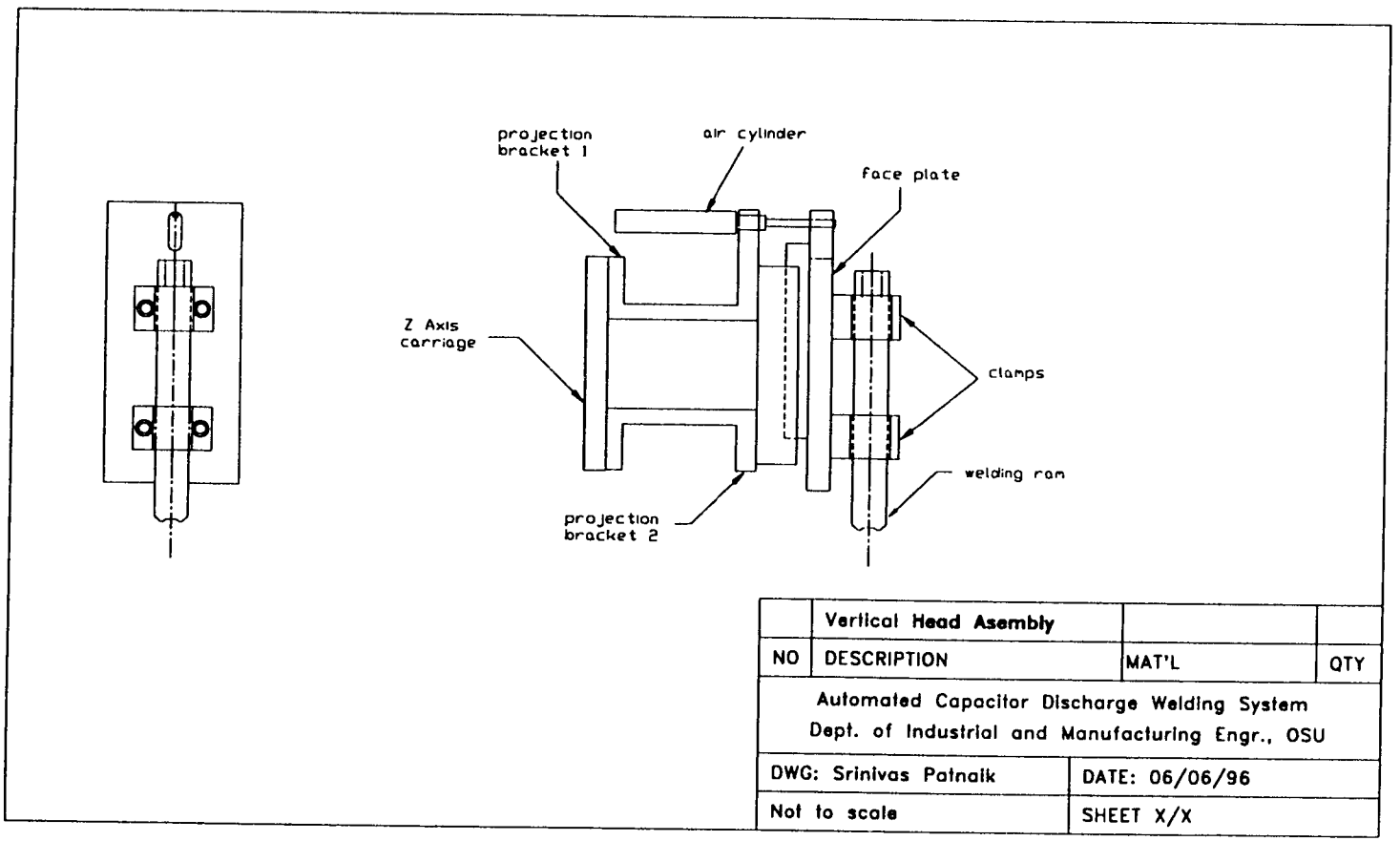

Figure B2 Welding head assembly

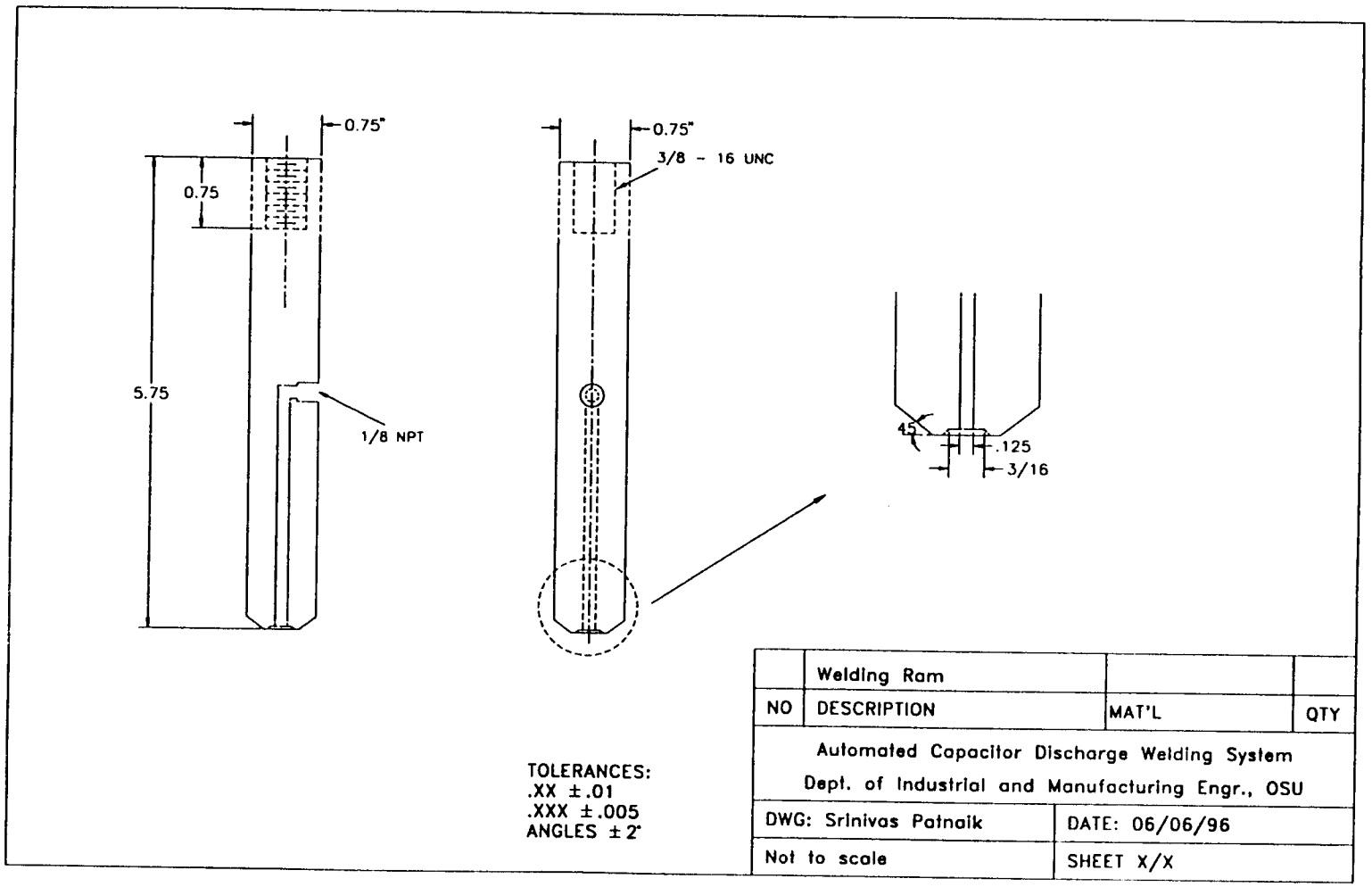

Figure B3 Welding Ram

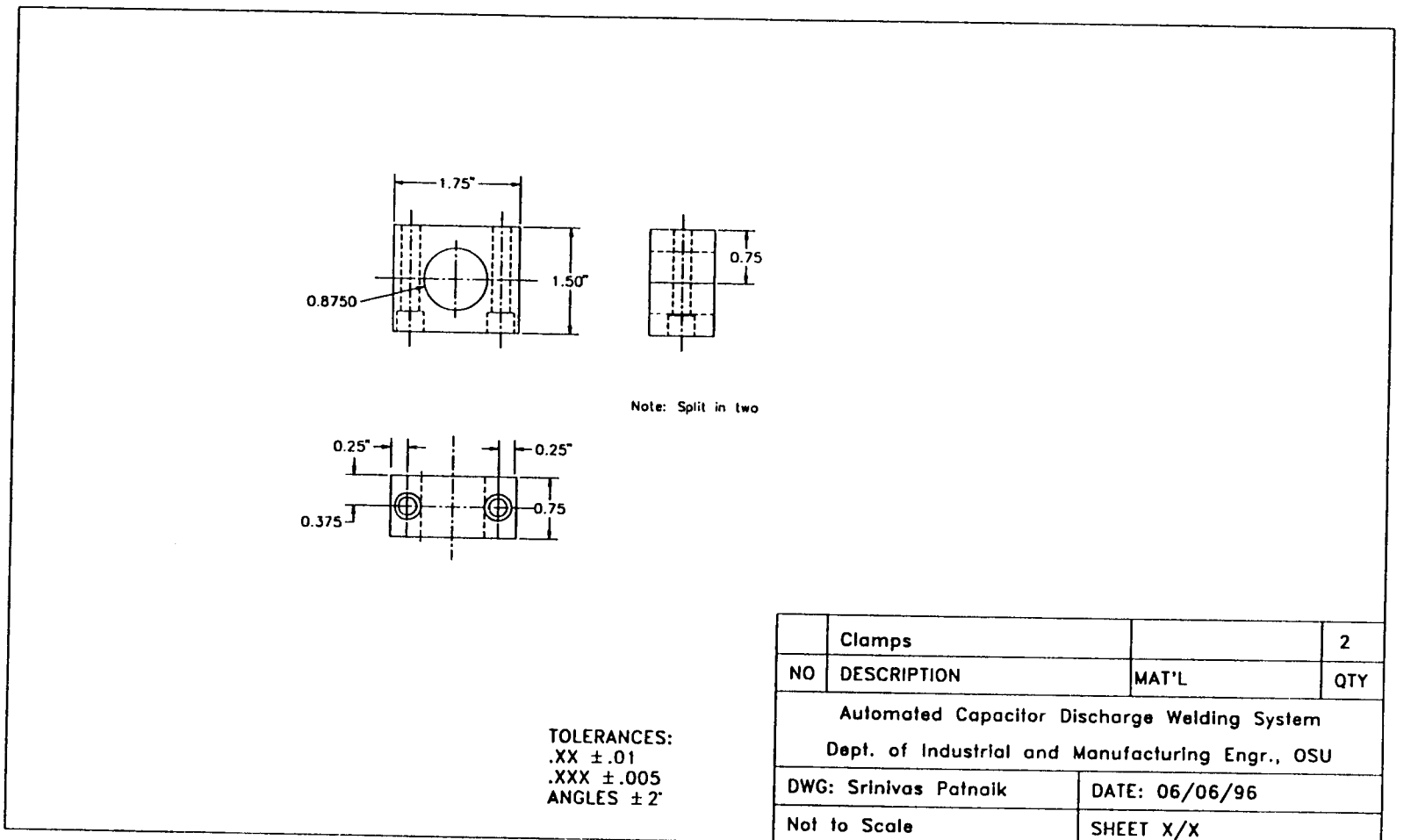

Figure B4 Clamps

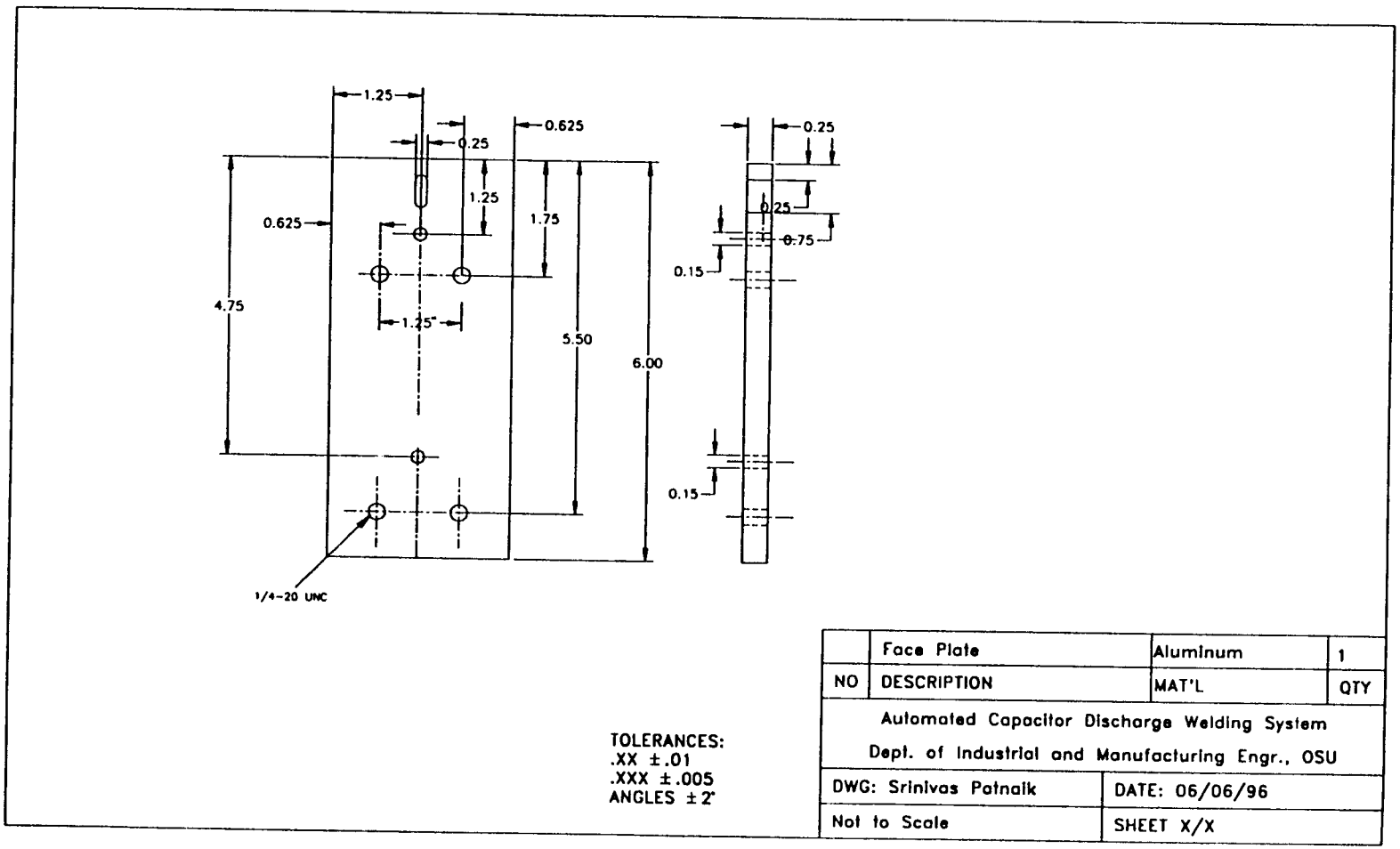

Figure B5 Face Plate

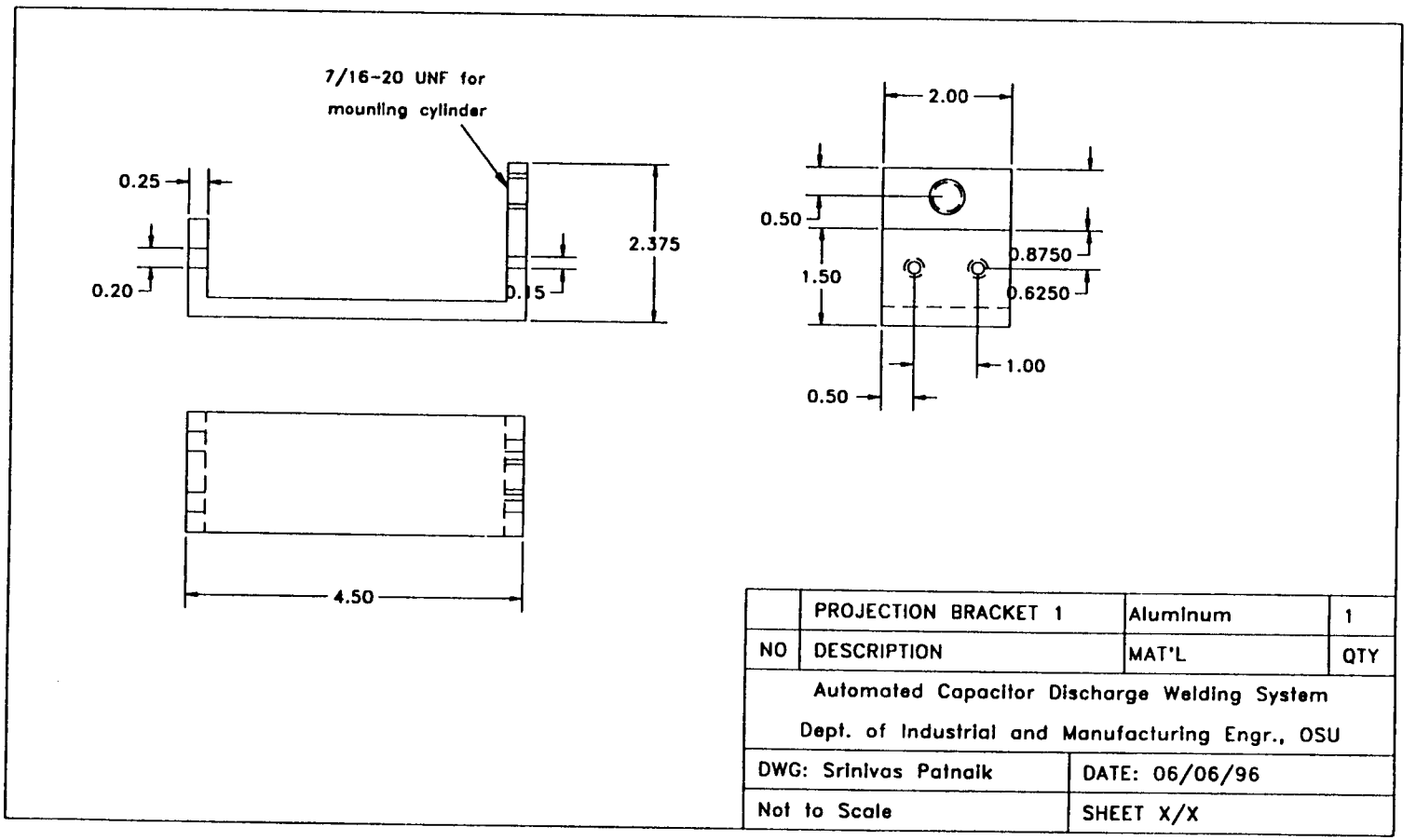

Figure B6 Projection Bracket 1

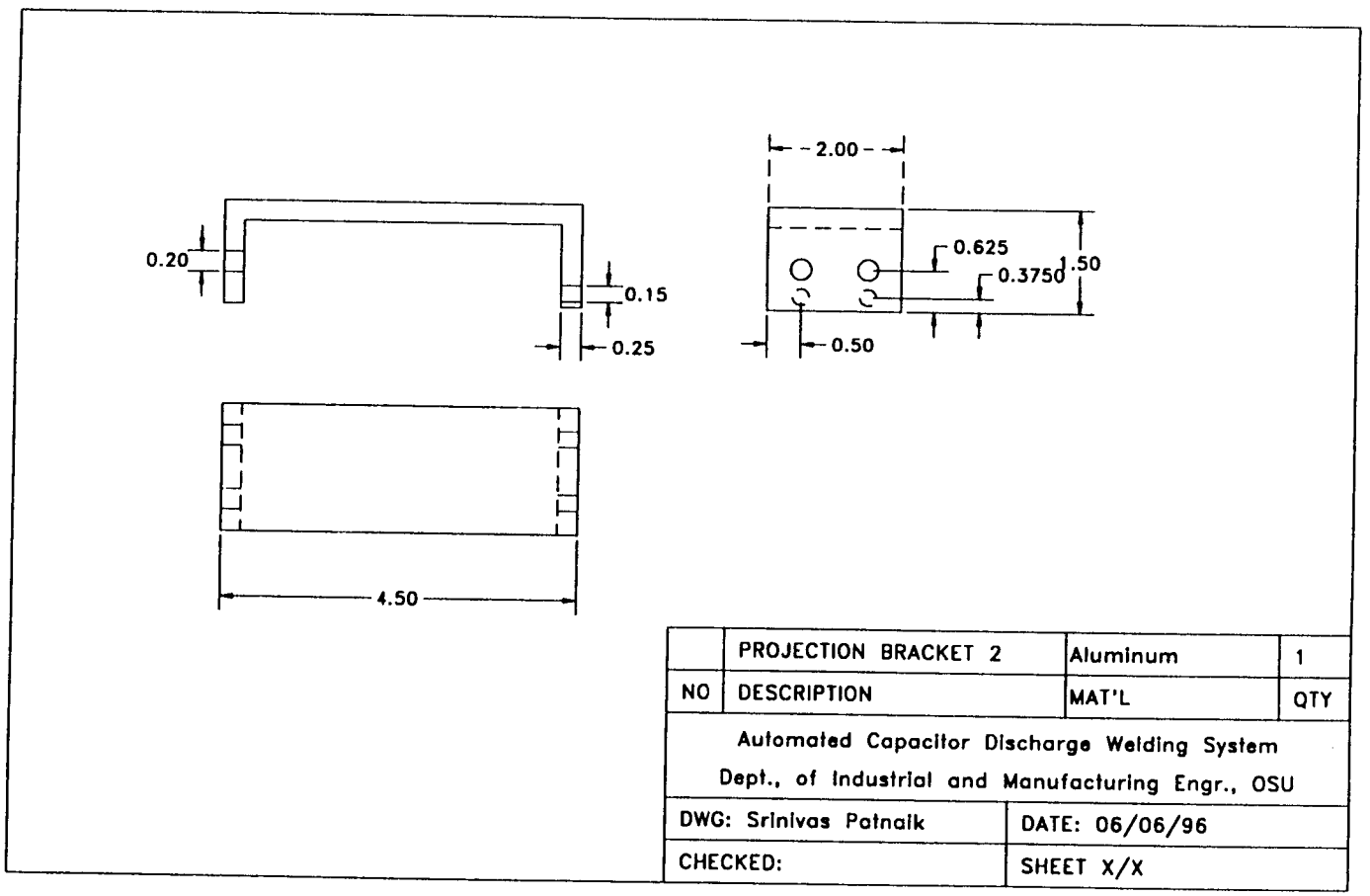

Figure B7 Projection Bracket 2

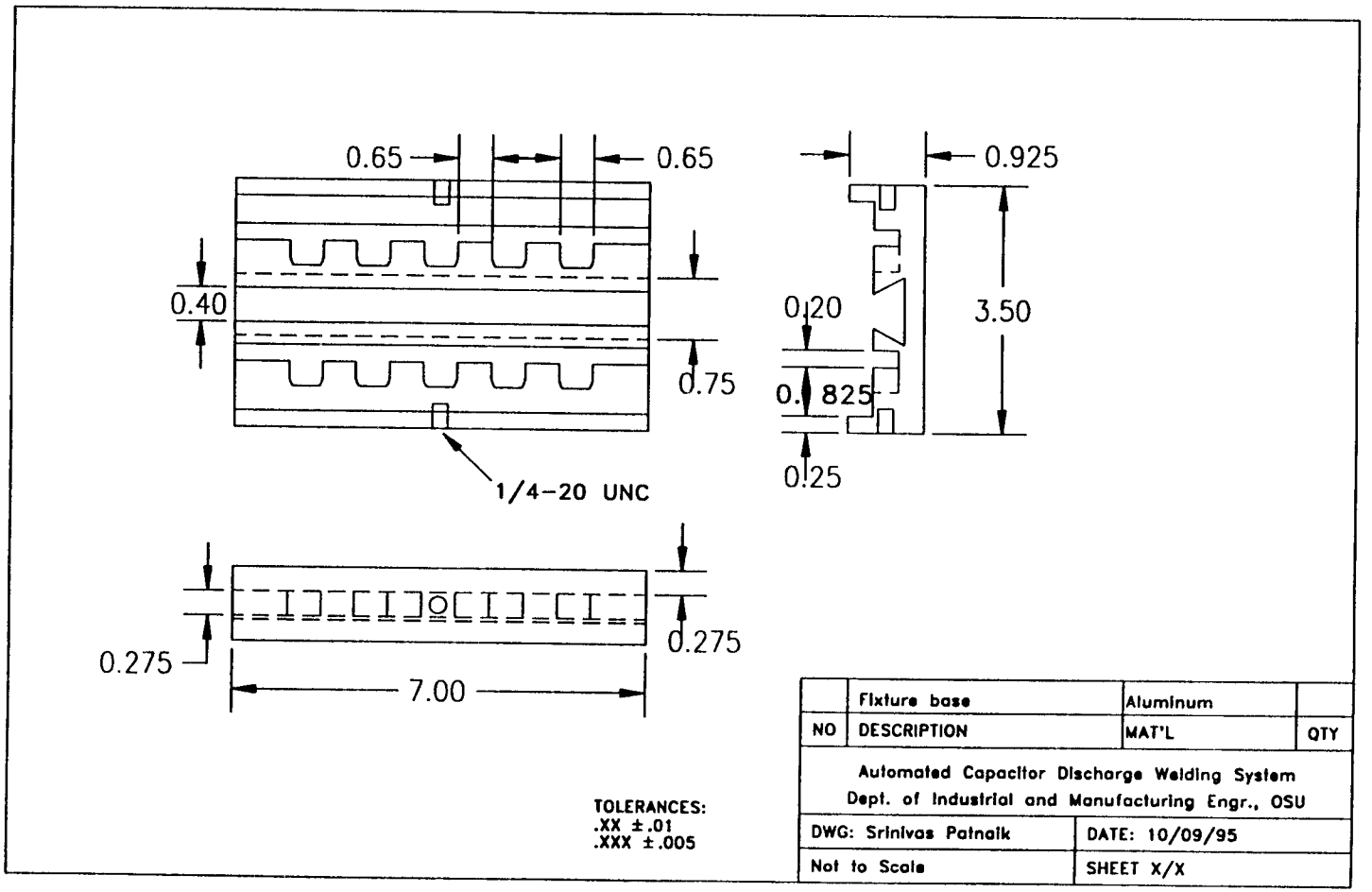

Figure B8 Fixture Base Plate

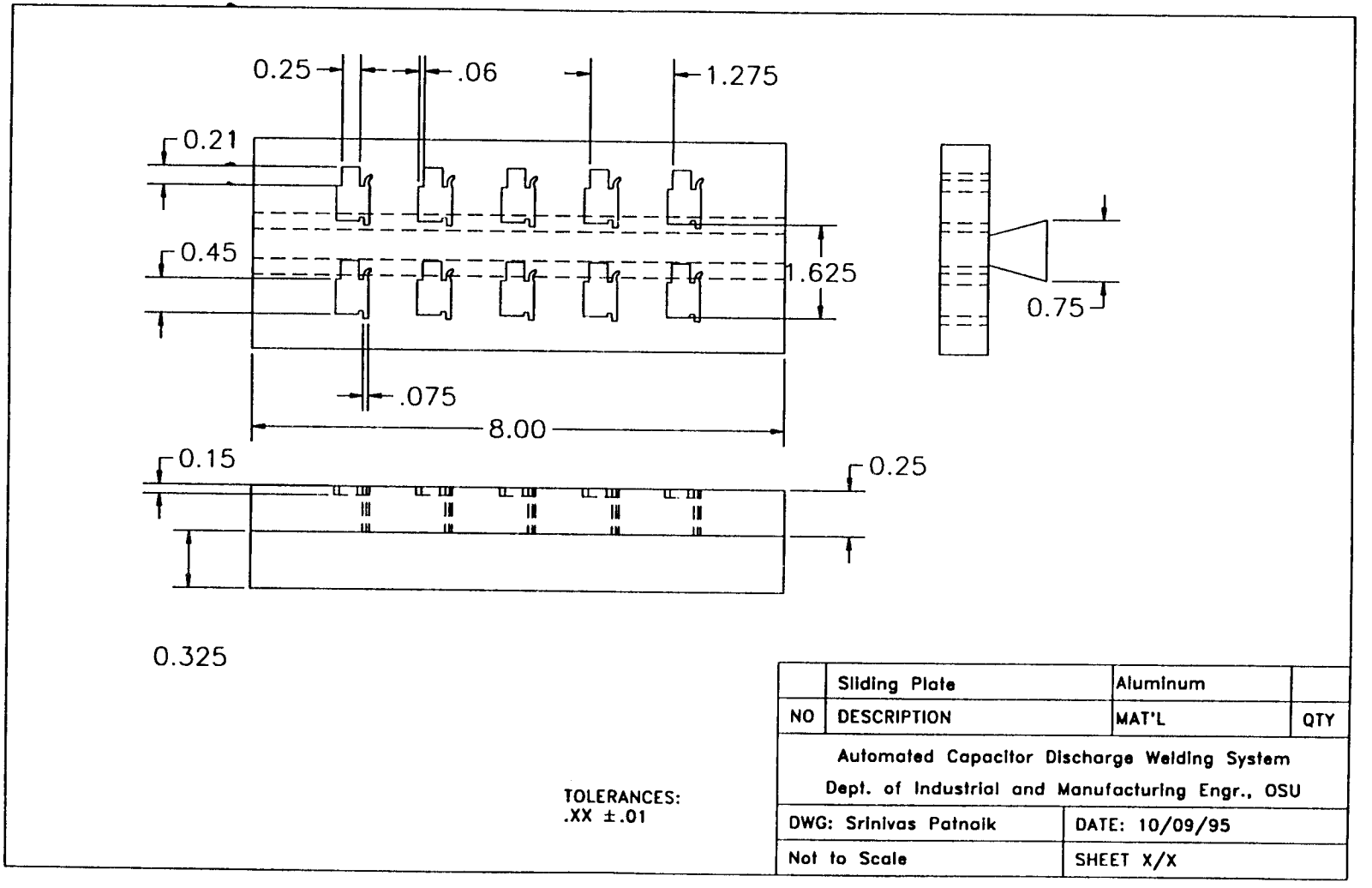

Figure B9 Fixture Sliding Plate

APPENDIX C
DESIGN CALCULATIONS

C1. CALCULATION OF THE SUCTION HOLE DIAMETER FOR THE WELDING RAM

Since vacuum chucking was implemented for the silver contact pick-up, the hole drilled through the welding ram had to be large enough to provide good suction for the pick-up while maximizing the area of contact between the welding ram and the silver contact (for the conduction of high current). Hence the suction hole diameter had to be optimized for these requirements.

Figure C1 is a free-body diagram of the silver contact. The suction force (or force due to vacuum, F_v) should be greater than or equal to the force due to the weight (F_w)of the silver contact.

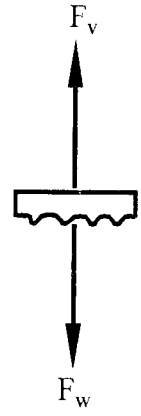

Figure C1 Free body diagram of the silver contact

$$F_v = F_w \tag{c1.1}$$

F_v is calculated in the following way:

$$F_v = A_{cs} \times P_b = (\pi/4)\, d^2 P_b \tag{c1.2}$$

where A_{cs} is the area of cross section of the hole, P_b is the back pressure due to vacuum, and d is the diameter of the hole. Substituting the value of F_v in equation (c1.1),

$$(\pi/4)\, d^2 P_b = F_w$$

Therefore,

$$d = \sqrt{\frac{4F_w}{\pi P_b}} \qquad (c1.3)$$

Let ρ_{Ag} represent the density of silver and V_{silver} the volume of silver (contact), then F_w can be calculated as follows:

$$F_w = \rho_{Ag} \times V_{silver} \qquad (c1.4)$$

and $$V_{silver} = (\pi/4)\, d^2_{\text{silver contact}}\, t$$

where $d_{\text{silver contact}}$ and t are the diameter and thickness of the silver contact respectively. From tables, $\rho_{Ag} = .38$ lb./in^3. Therefore,

$$V_{silver} = (\pi/4)\,(.154)^2\,(.058) = 1.1 \times 10^{-3}\ \text{in}^3 \text{ and}$$

$$F_w = .38 \times 1.1 \times 10^{-3} = 4.1 \times 10^{-4}\ \text{lb.}$$

Back pressure, P_b is the difference between the atmospheric pressure (P_a = 29.9 in. Hg) and (negative) pressure due to vacuum (P_v = 20 in Hg). Therefore,

$$P_b = P_a - P_v = 29.9 - 20 = 9.9 \text{ in Hg} = 1.914 \text{ psi}$$

Substituting the value of F_w and P_b in equation (c1.3), the value of d is obtained,

$$d = 0.0165 \text{ in.}$$

Assuming a safety factor of 3, the suction diameter in the welding ram = .05 in.

C2. CALCULATION OF THE THEORETICAL AND ACTUAL WELD AREAS OBTAINED FROM THE CORRUGATED SIDE OF SILVER CONTACT

The weld area that is obtained when the corrugated side of the silver contact is welded to brass is the area of the corrugations that is available after flash is expelled (i.e. area of the circle with radius a, Figure C2). The thermodynamic weld energy calculations were performed for a theoretical loss of 8.6 moles/m^2 of metal in the form of flash (Wilson, 1996). This was used for the theoretical weld area calculation. Assuming equal amounts from both metals, the (theoretical) amount of flash from silver is 4.3 moles/m^2. The diameter of the silver contact is 3.91×10^{-3} m. Therefore, number of moles expelled in the form of flash, M is:

$$M = 8.6 \times (\pi/4) \times (3.91 \times 10^{-3})^2 = 1.03 \times 10^{-4} \text{ moles.} \quad \text{(c2.1)}$$

Assuming equal amounts from both metals, the number of moles from silver is 5.16×10^{-5} moles. From tables, molecular weight of Silver is 107.86 g/mol. Therefore the mass of silver flash, m, is :

$$m = \text{no. of moles} \times \text{molecular weight} = 5.16 \times 10^{-5} \times 107.86 = .005 \text{ gms} \quad \text{(c2.2)}$$

From tables, density of Silver

$$\rho_{Ag} = 10.5 \text{ g/cc}$$

Therefore, (theoretical) volume of metal expelled in the form of flash from each corrugation (V_{tc}) is

$$V_{tc} = 0.005/10.5 = 3.97 \times 10^{-5} \text{ cc.} \quad \text{(c2.3)}$$

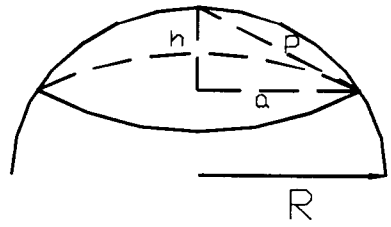

Figure C2 A hemispherical corrugation on the Silver contact

Assuming a corrugation to be a perfect hemisphere, the radius was measured to be 0.038cm. This was measured from the photomicrographs using simple geometry. The (theoretical) weld area available with the corrugated side being welded to brass is the area of the corrugation that is left after the flash is expelled. Hence we need to find the section of the hemisphere (Figure C2) whose volume is equal to the volume of flash V_{tc}.

From Figure C2, the volume of segment

$$V = 1/3\ \pi h^2 (3R - h) = 1/6\ \pi h\ (3a^2 + h^2) \qquad \text{(c2.4)}$$

Therefore,

$$V = 1/3\ \pi h^2 (3 \times 0.038 - h) \qquad \text{(c2.5)}$$

Solving for h, $h3 - 0.114h^2 + 3.79 \times 10^{-5} = 0$ (c2.6)

Solving the Cubic equation, we get three values for h. One out of the three values is a feasible solution, h = .02 cm. Now the value of 'a' has to be calculated in order to find the circular cross sectional area that is available for weld. Substituting the value of 'h' in equation (c2.4),

$3.79 \times 10^{-5} = 1/6\pi(.02)(3a^2 + .02^2)$

a = .033 cm.

Weld area from one corrugation = $\pi a^2 = 3.42 \times 10^{-3}\ cm^2$ (c2.7)

Theoretical weld area obtained with the corrugated side down = $12 \times 3.42 \times 10^{-3}$

$= .041\ cm^2$.

The actual amount of flash expelled in a weld was found to be .006 gms. This was obtained by measuring the difference in the weights of the sample before and after the weld. Assuming equal masses removed from both metals, the amount of flash expelled by silver is 0.003 gms. The same weld area calculations were performed as above. The weld area was found to be .034 cm^2 which is nearly 83% of the theoretical weld area. The excess energy must have dissipated in the form of light, sound and electro-magnetic forces.